EMERGY and Environmental Accounting
Organization of Lecture:

- Brief review of the concepts of energy hierarchy and definitions of emergy and related quantities.
- Overview of global emergy flows
- Emergy and transformities of many products and processes of the biosphere
Emergy Concepts and Principles...

Emergy, transformity, specific emergy, relationship to money, etc...
ENERGY...

The ability to cause work.

Since all energy can be converted 100% to heat, it is convenient to express energy in heat units...btu's calories, joules.
There are many “forms” of energy…

- Sunlight…
- Wind…
- Geopotential energy of elevated water…
- Fuel…
- Electricity…
- Information…
Not all forms of energy are equivalent...

sunlight ≠ wind ≠ fuels ≠ electricity

While they can all be converted to heat... one cannot say that calories of one form of energy are equal to calories of another form in their ability to cause work...
Work may be thought of as an energy transformation process… two or more energies are “processed” to make another form of energy.
Energy Quality...

- related to concentration.
- flexibility
- ease of transportation
- convertibility
Energy Quality...

- The concept of quality required a new concept of energy.
- A concept of energy that recognized that not all forms of energy have the same qualities
- A quantitative means of measuring quality....
EMERGY – The available energy (exergy) of one form previously used up directly and indirectly to make a service or product.

Expressed in energy of the same FORM ... usually solar energy

Sometimes called Energy Memory = Emergy

Similar to Embodied Energy

Units = Solar Emjoules = sej
Related Concepts…

EMPOWER = emergy per time
EMPOWER Intensity = empower per area
EMERGY - The available energy (of one form) required directly and indirectly to make something.
Units of EMERGY...

Solar emjoules...

or “sej”
Hierarchy...

A hierarchy is a form of organization resembling a pyramid where each level is subordinate to the one above it.

...in ecology, hierarchical organization is a group of processes arranged in order of rank or class in which the functions at each higher level become more broadly embracing than at the lower level.

Thus we often speak of food-chains as hierarchical in organization.
All systems are organized as hierarchies.

Many small components and fewer and fewer larger components.
Food chain...with each successive energy transformation, there is less energy, but of a higher quality.
Energy Chain... the food chain can be thought of as an energy transformation chain. At each transformation step some energy is degraded and some is passed to the next step in the chain.
The 20th century energy food chain of techno-humans...
Unit Emergy Values (UEVs)...

The amount of emergy required to produce a given amount of mass or energy of a product

\[ \text{UEV} = \frac{\text{Output in Emergy}}{\text{Output (joules or grams)}} \]
If units are sej/J it is called Transformity.

If units are sej/g it is called Specific Emergy.

We also use sej/$.
Unit Emergy Values are a kind of efficiency measure, since they relate all the outputs from processes to their inputs.

The lower the transformity or specific emergy the more efficient the conversion.
Hierarchical Levels – UEVs indicate Quality
Parallel Processes – UEVs indicate efficiency
Emergy Concepts and Principles...

Emergy and Solar Transformity...
Unit Emergy Values...

Solar transformity of Production = Solar Emergy / Exergy

\[ T_{r_p} = \frac{2.0 \times 10^6 \text{sej}}{2 \text{ J}} = 1 \times 10^6 \text{ sej/J} \]

Solar transformity of Material Cycle = Solar Emergy / Exergy

\[ T_{r_{mc}} = \frac{2.0 \times 10^6 \text{sej}}{0.002 \text{ J}} = 1 \times 10^9 \text{ sej/J} \]
Emergy Concepts and Principles...

Unit Emergy Values...

Emergy = Exergy * UEV

So by definition the emergy of a flow can be calculated by multiplying the exergy (or mass) of the flow by its UEV

1E 6 grams oil * Sp_{oil} = Emergy in the oil

2E5 joules oil * Tr_{oil} = Emergy in the oil
### Solar Transformities

<table>
<thead>
<tr>
<th></th>
<th>Solar emjoules per joule (sej/J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunlight</td>
<td>1</td>
</tr>
<tr>
<td>Plant production</td>
<td>6,700</td>
</tr>
<tr>
<td>Wood</td>
<td>36,000</td>
</tr>
<tr>
<td>Coal</td>
<td>97,000</td>
</tr>
<tr>
<td>Oil</td>
<td>148,000</td>
</tr>
<tr>
<td>Electricity</td>
<td>500,000</td>
</tr>
</tbody>
</table>
The Emergy Baseline
Three main flows driving global processes, Sunlight, Tidal Exergy, and Deep Heat
Total Emergy = Solar Emergy + Tidal Emergy + Deep Earth Heat Emergy

Recall: Solar emergy = exergy flow * transformity

By definition the Emergy from Solar input has transformity = 1.0

Transformities for the other two exergy sources must be calculated
Table 1. Annual Emergy Contributions to Global Processes* (after Odum et al. 2000)

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

Total Emergy driving the geobiosphere = 15.83 E24 sej/yr

(Odum, 2000)
Solar Emergy...

Solar energy flow: $3.93 \times 10^24$ J/yr based on solar constant $2 \text{ gcal/cm}^2/\text{min}$, 70% absorption, and $1.27 \times 10^{14}$ m$^2$ cross section facing the sun.

\[
\text{Solar Energy} = 2\text{cal/cm}^2/\text{min} \times 5.26 \times 10^5 \text{min/yr} \times 0.70 \times 1.27 \times 10^{14} \text{m}^2 \times 10^4 \text{cm}^2/\text{m}^2 = 3.93 \times 10^24 \text{ J/yr}
\]

SolarTransformity = 1.0 sej/J by definition
The tidal emergy and emergy of deep heat can be calculated using two equations with two unknowns

1. Transformity of tidal momentum
2. Transformity of deep heat
The main processes contributing 13.21 $\text{E}20$ J/yr heat to the earth's crust as given by Sclater et al. (1980).

By subtracting the estimate for radioactivity generation (1.98 $\text{E}20$ J/yr) and heat flux up from the mantle (4.74 $\text{E}20$ J/yr), the remaining annual flow of 6.49 $\text{E}20$ J/yr can be attributed to the sources from above, the sun and tide that drive the atmosphere, ocean, hydrological, and sedimentary cycles.
Empower Supporting the Geobiosphere….

Transformity of Deep Heat

Solar emergy + Tidal emergy = Emergy of the heat generated by the surface processes

\[
39,300 \times 10^{20} \text{ J/yr}(1 \text{ sej/J}) + (0.52 \times 10^{20} \text{ J/yr}) \times T_r_t = (6.49 \times 10^{20}) \times T_r_h \quad (1)
\]
The emergy budget equation for oceanic geopotential energy includes solar emergy, tidal emergy, and the contribution of the earth to the global process.

The earth contributes $6.72 \times 10^{20}$ J/yr...

4.74 $\times 10^{20}$ J/yr deep heat and 1.98 $\times 10^{20}$ J/yr radioactive heat.
Solar emergy + Tidal emergy + Deep Earth emergy = Oceanic geop. emergy

\[(39,300 \times 10^{20}) \times 1.0 + (0.52 \times 10^{20}) \times Tr_t + (6.72 \times 10^{20}) \times Tr_h = (2.14 \times 10^{20}) \times Tr_t \quad (2)\]
Combining Equations
To obtain the unit emergy values (solar transformities), equation (1) was subtracted from equation (2) to obtain:

\[
(39,300 \text{ E20}) \times 1.0 + (0.52 \text{ E20}) \times Tr_t + (6.72 \text{ E20}) \times Tr_h = (2.14 \text{ E20}) \times Tr_t \\
-(39,300 \text{ E20 J/yr})(1 \text{ sej/J}) - (0.52 \text{ E20 J/yr}) \times Tr_t = -(6.49 \text{ E20}) \times Tr_h \\
(6.72 \text{ E20}) \times Tr_h = (2.14 \text{ E20}) \times Tr_t - (6.49 \text{ E20}) \times Tr_h
\]

\[
Tr_t = 6.17 \times Tr_h
\]
Substituting $(\text{Tr}_t = 6.17 \text{ Tr}_h)$ in equation 1

$\left(39,300 \text{ E20 J/yr}\right)(1 \text{ sej/J}) + \left(0.52 \text{ E20 J/yr}\right)\text{Tr}_t = (6.49 \text{ E20}) \text{ Tr}_h$

$\left(39,300 \text{ E20 J/yr}\right)(1 \text{ sej/J}) + \left(0.52 \text{ E20 J/yr}\right)\times 6.17 \text{ Tr}_h = (6.49 \text{ E20}) \text{ Tr}_h$

to obtain the solar transformity of crustal heat:

$\text{Tr}_h = 11,981 \text{ sej/J}$

and

$\text{Tr}_t = 6.17 \times 11,981 = 73,927 \text{ sej/J}$
<table>
<thead>
<tr>
<th>Note</th>
<th>Input</th>
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</tr>
</tbody>
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*Table 1. Annual Emergy Contributions to Global Processes* (after Odum et al. 2000)
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 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,*


In addition, two other papers address important related issues:


But first....
A note about units and nomenclature
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)

$T_R = \text{Transformity (sej/J)}$
Brown, and Ulgiati. Assessing the Global Environmental Sources Driving the Geobiosphere: A Revised Emergy Baseline.

Diagrams describing the relationships between global exergy sources generating:

(a) the exergy of crustal heat and (b) the exergy of ocean geopotential.
Brown, and Ulgiati. Assessing the Global Environmental Sources Driving the Geobiosphere: A Revised Emergy Baseline.

Results of the Monte Carlo simulation of the geobiosphere energy equations:

- Resulting solar equivalence ratios (top) and
- Solar equivalent exergy (bottom)
Transformities and empower from previous evaluation compared with SER and solar equivalent exergy of this restudy

<table>
<thead>
<tr>
<th>Inflow</th>
<th>Brown &amp; Ulgiati (2010)</th>
<th>This Restudy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exergy</td>
<td>UEV (sej J(^{-1}))</td>
</tr>
<tr>
<td>Solar energy absorbed</td>
<td>3.59E+24</td>
<td>1</td>
</tr>
<tr>
<td>Geothermal sources</td>
<td>1.63E+20</td>
<td>20,300</td>
</tr>
<tr>
<td>Tidal energy absorbed</td>
<td>1.17E+21</td>
<td>72,400</td>
</tr>
<tr>
<td>Total global empower(^b)</td>
<td>(\frac{15.2}{12.1 (1.51)})</td>
<td>15.2</td>
</tr>
</tbody>
</table>
Campbell, 2016. Emergy Baseline for the Earth: Review of the Science and a New Calculation

Diagram of the generation of the geopotential energy of the world oceans (ice covered polar oceans)

Solar Emergy + Gravitational Emergy = Emergy of Ocean Geopotential
(38,540 E20 J/yr ) (1 semj J⁻¹) + (1.105 E20 J yr⁻¹)(τ₆) = (2.194 E +20 J yr⁻¹ ) (τ₆)
τ₆ = 35,400 semj J⁻¹
Campbell, 2016. Emergy Baseline for the Earth: Review of the Science and a New Calculation

Diagram of deep Earth heat driving the tectonic processes of the Earth Cycle

Solar exergy transformity of erosion = 38491/0.000886 = 4.3444E+7 semj J⁻¹
Earth exergy transformity uplift = 9.25/0.000886 = 1.0440E+4 semj J⁻¹
Ratio solar exergy to Earth exergy = 4.3444E+7 semj J⁻¹ ÷ 1.0440E+4 semj J⁻¹ = 4161
Exergy inflows to the Earth as solar radiation, the deep Earth heat driving tectonic processes and the tidal geopotential exergy dissipated in the world oceans.
### Exergy, Solar Equivalent Ratios and Solar Equivalent Exergy of the GEB

<table>
<thead>
<tr>
<th>Energy source</th>
<th>Exergy Inflow (J y(^{-1}))</th>
<th>SER (seJ J(^{-1}))</th>
<th>Solar Equivalent Exergy (seJ y(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar radiation</td>
<td>3.849x10(^{24})</td>
<td>1</td>
<td>3.849x10(^{24})</td>
</tr>
<tr>
<td>Ocean tidal dissipation</td>
<td>1.11x10(^{20})</td>
<td>35400</td>
<td>3.924x10(^{24})</td>
</tr>
<tr>
<td>Earth's tectonic heat</td>
<td>9.247x10(^{20})</td>
<td>4162</td>
<td>3.849x10(^{24})</td>
</tr>
<tr>
<td>Total Emergy Inflow</td>
<td></td>
<td></td>
<td>1.163x10(^{25})</td>
</tr>
</tbody>
</table>

Solar Equivalence Ratios for Radionuclides

<table>
<thead>
<tr>
<th>Isotope</th>
<th>SER (seJ/J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{40}$K</td>
<td>8.2E+3</td>
</tr>
<tr>
<td>$^{232}$Th</td>
<td>4.2E+3</td>
</tr>
<tr>
<td>$^{235}$U</td>
<td>3.9E+3</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>3.7E+3</td>
</tr>
</tbody>
</table>

Diagram of the accretion process generating Earth's primordial heat ($G_{E,O}$) and rotational kinetic energy ($K_{E,O}$).
Five alternative configurations to assign gravitational potential energy to Earth rotational KE and primordial heat.

<table>
<thead>
<tr>
<th>Method</th>
<th>Renocation of dissipation</th>
<th>Diagram</th>
<th>Mathematical effect</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>By-product (1)</td>
<td>Separately to rotational energy and primordial heat according to literature values for the efficiency of their production processes</td>
<td><img src="image1" alt="Diagram" /></td>
<td>$\gamma_p = \gamma_A$&lt;br&gt;$\gamma_{p1} &lt; 1 \text{ gej/j}$</td>
<td>Additive.</td>
<td>Values unknown.</td>
</tr>
<tr>
<td>By-product (2)</td>
<td>Total GPE assigned to primordial heat</td>
<td><img src="image2" alt="Diagram" /></td>
<td>$\gamma_p &gt; \gamma_{A} = 1 \text{ gej/j}$</td>
<td>Additive.</td>
<td>Unfalsifiable analyst decision.</td>
</tr>
<tr>
<td>By-product (3)</td>
<td>Total GPE assigned to rotational energy</td>
<td><img src="image3" alt="Diagram" /></td>
<td>$\gamma_p = \gamma_{A} &gt; 1 \text{ gej/j}$</td>
<td>Additive.</td>
<td>Unfalsifiable analyst decision.</td>
</tr>
<tr>
<td>Split</td>
<td>GPE of each flow is proportional to the exergy of each final storage.</td>
<td><img src="image4" alt="Diagram" /></td>
<td>$\gamma_p = \gamma_A$&lt;br&gt;$\gamma_{p1} &lt; 1 \text{ gej/j}$</td>
<td>Additive.</td>
<td>No quality distinction between heat and rotational energy.</td>
</tr>
<tr>
<td>Co-product</td>
<td>Total GPE allocated to both outputs,</td>
<td><img src="image5" alt="Diagram" /></td>
<td>$\gamma_p = \gamma_A$&lt;br&gt;$\gamma_{p1} &gt; 1 \text{ gej/j}$</td>
<td>Most simplistic.</td>
<td>Co-products cannot be added.</td>
</tr>
</tbody>
</table>
Exergy, solar equivalent ratios and solar equivalent exergy contribution of the radioisotopes

<table>
<thead>
<tr>
<th>Isotope</th>
<th>(TW)</th>
<th>Exergy Contribution (E20 J yr⁻¹)</th>
<th>SER¹. (seJ J⁻¹)</th>
<th>Solar Eq. Exergy Contribution (seJ y⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>238U</td>
<td>6.3</td>
<td>2.0E+20</td>
<td>3.70E+03</td>
<td>7.3E+23</td>
</tr>
<tr>
<td>232Th</td>
<td>6.3</td>
<td>2.0E+20</td>
<td>4.20E+03</td>
<td>8.3E+23</td>
</tr>
<tr>
<td>40K</td>
<td>3.1</td>
<td>9.9E+19</td>
<td>8.20E+03</td>
<td>8.1E+23</td>
</tr>
<tr>
<td>Total:</td>
<td>15.7</td>
<td><strong>4.9E+20</strong></td>
<td><strong>4.60E+03</strong></td>
<td><strong>2.27E+24</strong></td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Source</th>
<th>Exergy (J y(^{-1}))</th>
<th>SER (seJ J(^{-1}))</th>
<th>Solar Equivalent Exergy (seJ y(^{-1}))</th>
<th>By-Product #2</th>
<th>Solar Equivalent Exergy (seJ y(^{-1}))</th>
<th>Split</th>
<th>Solar Equivalent Exergy (seJ y(^{-1}))</th>
<th>Co-product</th>
<th>Solar Equivalent Exergy (seJ y(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunlight Primordial</td>
<td>3.60E+24</td>
<td>?</td>
<td>?</td>
<td>1</td>
<td>3.60E+24</td>
<td>1</td>
<td>3.60E+24</td>
<td>1</td>
<td>3.60E+24</td>
</tr>
<tr>
<td>Heat Radiogenic Heat</td>
<td>5.32E+20</td>
<td>?</td>
<td>?</td>
<td>14400</td>
<td>1.52E+23</td>
<td>1300</td>
<td>4.76E+24</td>
<td>11100</td>
<td>5.22E+24</td>
</tr>
<tr>
<td>GEB</td>
<td>1.17E+20</td>
<td>?</td>
<td>?</td>
<td>1300</td>
<td>2.28E+24</td>
<td>40700</td>
<td>2.28E+24</td>
<td>11100</td>
<td>2.28E+24</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>44600</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Inflow</th>
<th>Brown and Ulgiati</th>
<th>Campbell</th>
<th>De Vilbiss et al.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exergy (seJ J(^{-1}))</td>
<td>Solar Equivalent Exergy (E(^{+24}) seJ yr(^{-1}))</td>
<td>Exergy (seJ J(^{-1}))</td>
</tr>
<tr>
<td>Solar energy absorbed</td>
<td>3.60E+24</td>
<td>1</td>
<td>3.85E+24</td>
</tr>
<tr>
<td>Geothermal Flows(^a)</td>
<td>9.78E+20</td>
<td>5,500 (985)</td>
<td>9.20E+20</td>
</tr>
<tr>
<td>Primordial Heat</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiogenic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tidal energy absorbed</td>
<td>1.17E+20</td>
<td>26,300 (3800)</td>
<td>1.11E+20</td>
</tr>
<tr>
<td>Total global empower</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\): Geothermal Flows include geothermal energy from mantle upwelling, which is estimated to be 9.78E + 20 seJ J\(^{-1}\) or 5.50e + 20 seJ J\(^{-1}\) in 1985.

\(^b\): SER\(^b\) for Geothermal Flows is 7.500 E\(^{+24}\) seJ J\(^{-1}\).

\(^c\): Total global empowerment is 11.6 up to 13.5 when solar baselines are added.
Summary of GEB and Solar Equivalence Ratios and Solar Equivalent Exergy derived from Brown & Ulgiati, Campbell & DeVilbiss et al.

<table>
<thead>
<tr>
<th>Inflow</th>
<th>Exergy(^a)</th>
<th>SER(^b) (seJ J(^{-1}))</th>
<th>Solar Equivalent Exergy(^c) (E+24 seJ yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar energy absorbed</td>
<td>3.73E+24</td>
<td>1</td>
<td>3.7</td>
</tr>
<tr>
<td>Geothermal Flows</td>
<td>9.52E+20</td>
<td>4,900</td>
<td>4.7</td>
</tr>
<tr>
<td>Tidal energy absorbed</td>
<td>1.14E+20</td>
<td>30,900</td>
<td>3.5</td>
</tr>
<tr>
<td>Total Global Empower</td>
<td></td>
<td></td>
<td>12.0</td>
</tr>
</tbody>
</table>

b. Average of the SERs from Brown & Ulgiati (2016), Campbell (2016)
c. Rounded to two significant figures
Questions?

Comments?

Concerns?