Environmental Accounting
and EMERGY SYNTHESIS

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Howard T. Odum (1924 - 2002)

He introduced a unifying systems theory based on
the laws of thermodynamics

Originally developed to
study eco-systems,
but it can be applied to
any system
For his epochal contributions in systems ecology prof. H.T. Odum (together with his brother E.P. Odum, also well known ecologist) was awarded the Crafoord Prize in the Biosciences in 1987 by the Royal Swedish Academy of Sciences.

The Crafoord Prize 1987

His Majesty the King of Sweden (to the right) together with (from the left) Mrs Elizabeth Odum, Mrs Martha Odum, the prizewinner Howard T. Odum, the donor Mrs Anna Greta Crafoord and the prizewinner Eugene P. Odum. Photo: Ilse Jonsson, Svensk reportagefotograf.

H.T.Oдум, Gainesville, Florida, 1990
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 = fuel = 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.
Direct Solar Radiation, Gravitational Energy and Deep Heat are the main Biosphere Driving Forces.

**Emergy Intensities**...

**EMERGY** - The energy (of one form) required directly and indirectly to make something

Emergy Intensity =

Emergy of the output

Output (Joules or grams)
Emergy Intensities...

Emergy intensities 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.

Units of EMERGY...

Solar emergy joules...

or Solar emjoules...

or “seJ”
Units of Emergy Intensities...

- If units are Sej/J they are called Transformities
- If units are sej/g they are called Specific Emergies
- We also use Sej/$, seJ/€, seJ/hr, seJ/person...generally indicated as “emergy intensities”
Food chain...with each successive energy transformation, there is less energy, but of a higher quality

Typical Solar Transformities

<table>
<thead>
<tr>
<th>Solar transformities</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>6,470</td>
</tr>
<tr>
<td>Wood</td>
<td>36,000</td>
</tr>
<tr>
<td>Coal</td>
<td>67,000</td>
</tr>
<tr>
<td>Oil</td>
<td>90,000</td>
</tr>
<tr>
<td>Electricity</td>
<td>300,000</td>
</tr>
</tbody>
</table>
During self-organization, systems are guided by the Maximum Empower Principle...

Self-organization tends to develop network connections that use energies in feedback actions to aid the process of getting more resources or using them more efficiently...

"In time, through the process of trial and error, complex patterns of structure and processes have evolved...the successful ones surviving because they use materials and energies well in their own maintenance, and compete well with other patterns that chance interposes."

H.T. Odum
Systems maximize power by: 1) developing storages of high-quality energy, 2) feeding back work from storages to increase inflows, 3) recycling materials as needed, 4) organizing control mechanisms that keep the system adapted and stable, 5) setting up exchanges for needed materials, 6) Contributing work to the next larger system.

Maximum Empower

All systems are organized hierarchically

Energy flows of the universe are organized in energy transformation hierarchies. Position in the energy hierarchy can be measured by the amount of energy required to produce something.
Energy Transformation Hierarchy

Spatial view of units and their territories. Many small components and fewer and fewer larger components.

Energy networks including transformation and feedbacks.

Aggregation of energy network into an energy chain

Bar graph of the energy flows

Bar graph of solar transformities

The energy chain...

At each transformation step some energy is degraded and some is passed to the next step in the chain.
Emergy accounting uses the thermodynamic basis of all forms of energy, materials and human services, but converts them into equivalents of one form of energy.

Emergy accounting is organized as a top down approach where first a system diagram of the process is drawn to organize the evaluation and account for all inputs and outflows.

Tables of the actual flows of materials, labor and energy are constructed from the diagram and all flows are evaluated.

The final step of an emegy evaluation involves interpreting the quantitative results.
In some cases, the evaluation is done to determine fitness of a development proposal. In others, it may be a question of comparing different alternatives, or the evaluation may be seeking the best use of resources to maximize economic vitality.

So the final step in the evaluation is to calculate several emergy indices that relate emergy flows of the system being evaluated to predict economic viability, carrying capacity, or fitness.

**Evaluating Alternatives...**

- In some cases, the evaluation is done to determine fitness of a development proposal.
- In others, it may be a question of comparing different alternatives, or
- the evaluation may be seeking the best use of resources to maximize economic vitality.

**Emergy Synthesis**

- Recently the evaluation process has been termed “Emergy Synthesis”.
- Synthesis is the act of combining elements into coherent wholes. Rather than dissect and break apart systems and build understanding from the pieces upward, emergy synthesis strives for understanding by grasping the wholeness of systems.
- By evaluating complex systems using emergy methods, the major inputs from the human economy and those coming “free” from the environment can be integrated to analyze questions of public policy and environmental management holistically.
1. **Left-right Energy Systems Diagram**

   Systems diagrams are used to show the inputs that are evaluated and summed to obtain the emergy of a resulting flow or storage.

   The purpose of the system diagram is to conduct a critical inventory of processes, storages and flows that are important to the system under consideration and are therefore necessary to evaluate.

2. **Preparation of an Emergy Evaluation Table**

   - Tables of the actual flows of materials, labor and energy are constructed from the diagram.
   - Raw data on flows and storage reserves are converted into emergy units, and then summed for a total emergy flow to the system.
Example emergy evaluation table...

<table>
<thead>
<tr>
<th>Note</th>
<th>Item</th>
<th>Data</th>
<th>Units</th>
<th>Emergy intensity (sej/unit)</th>
<th>Solar Emergy (E=15 sej/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>First item</td>
<td>xx.x</td>
<td>g or J/yr</td>
<td>xxx.x</td>
<td>xxx.x</td>
</tr>
<tr>
<td>2.</td>
<td>Second item</td>
<td>xx.x</td>
<td>g or J/yr</td>
<td>xxx.x</td>
<td>xxx.x</td>
</tr>
<tr>
<td>..</td>
<td>..</td>
<td>..</td>
<td>..</td>
<td>..</td>
<td>..</td>
</tr>
<tr>
<td>n.</td>
<td>n\textsuperscript{th} item</td>
<td>xx.x</td>
<td>g or J/yr</td>
<td>xxx.x</td>
<td>xxx.x</td>
</tr>
<tr>
<td>O.</td>
<td>Output</td>
<td>xx.xx</td>
<td>g or g/yr</td>
<td>xxx.x</td>
<td>$\frac{1}{n} \sum E_m$</td>
</tr>
</tbody>
</table>

\[ \text{Emergy of Storages} \]

- When calculating the emergy of stored quantities (storages), it is necessary to sum the emergy of each of the inputs for the time of its contribution.

- Input emergy inflows are multiplied by the time it takes to accumulate the storage and exported yield, if any.
Evaluations Based on Averaged Inputs

• All systems pulse... with time intervals and pulse strength that increase with scale.

• To evaluate a process on one scale of time and space usually means using averages for each of the inputs from smaller scales where pulses are of high frequency.

• For example, for an evaluation of phenomena on the scale of human economy, yearly averages are often appropriate.

Calculating Emergy Intensities

• After an evaluation table is prepared, emergy intensities of products can be calculated.

• The output or product (row "O" in the example table above) is evaluated first in units of energy or mass.

• Then the input emergy is summed and the emergy intensity for the product calculated by dividing the emergy by the units of the output.

• The emergy intensities that result are useful for other emergy evaluations.
EmDollars, EmEuros, ...
the money equivalent of emergy.

- By using a standard conversion factor, we can express emergy in currency equivalents...
- In the same way as we sometimes express money in energy equivalents...ie liters of gas
Relationship of money to emergy...
B. Review of concepts and definitions ...

**Emergy Benefit to Purchaser...**

\[
\text{EMERGY of product} \quad \frac{(\text{Energy flow})}{\text{(Transformation)}} = \frac{\text{Ratio of EMERGY to Money}}{\text{(Money paid)/(EMERGY/Currency)}} = \frac{\text{Benefit to Purchaser}}{\text{(Purchased energy/Currency)}}
\]

(a) Example:

- Price: $20/barrel
- 1 Barrel of Oil sold: 6.3 x 10^9 Joules/barrel
- (Energy flow): (5.3 x 10^4 sej)/(5.3 x 10^4 sej/16.69 $) = 13.1
- Ratio of EMERGY to Money: 13.1
- Benefit to Purchaser: 1.0 x 10^12 sej/yr

**Emergy/Money Ratio... USA, 2000**

Total Energy Input = 10.8 x 10^24 sej/yr

Input Energy A
Input Energy B
Input Energy C

Production
Gross Domestic Product
10.4 x 10^12 $

Consumption
People

GDP
10.4 x 10^12 $/yr

Total Energy = 10.8 x 10^24 sej/yr

= 1.0 x 10^12 sej/ $
Emdollars of the US Economy

Total Emergy Use
\[
\text{Gross Domestic Product} = 1.0 \text{ E12 sej/dollar}
\]

So...

Every dollar spent in US economy has "embodied" in it, 1 E 12 sej of emergy

Emergy/Money ratio...Italy, 2002

[Diagram showing emergy flows and emergy/money ratios]
Express emergy as Emdollars for ease of recognition...

An emergy input of $3.6 \times 10^{18} \text{ sej/yr}$... becomes $3.6 \times 10^6 \text{ Em$}$ in the USA

\[
\frac{3.6 \times 10^{18} \text{ sej/yr}}{1.0 \times 10^{12} \text{ sej/$}} = 3.6 \times 10^6 \text{ em$}
\]

while becomes...$1.5 \times 10^6 \text{ Em$}$ in Italy

Emergy Based Indicators.

What do they indicate...
Signatures

Signature of driving emergies for 1 hectare of corn in Florida (Brandt-Williams, 2002)

Signature of driving emergies for 1 hectare of Florida mangrove ecosystem (Brown and Bardi, 2001)

Emergy signature of Italy, 2002
Emergy Signature of Latvia, 2002

Large dependence on:

a) local renewable inputs
b) comparable amounts of imported fossil fuels and commodities other than fuels.

Emergy Signature of Denmark, 2002

Large dependence on:

a) fossil fuels (local and imported)
b) imports of goods and commodities other than fuels.
6. Performance Indicators

The systems diagram in Figure 2 shows non-renewable environmental contributions (N) as an emergy storage of materials, renewable environmental inputs (R), and inputs from the economy as purchased (F) goods and services.

Several ratios, or indices are given in Figure 1 that are used to evaluate the global performance of a process as follows:

**Emergy yield ratio.** The ratio of the emergy yield from a process to the emergy costs. The ratio is a measure of how much a process will contribute to the economy.
**Environmental loading ratio.** The ratio of nonrenewable and imported emergy use to renewable emergy use. It is an indicator of the pressure of a transformation process on the environment and can be considered a measure of ecosystem stress due to a production (transformation activity).

**Emergy Sustainability Index.** The ratio of the Emergy Yield Ratio to the Environmental Loading Ratio. It measures the contribution of a resource or process to the economy per unit of environmental loading.
**Emergy Investment ratio.** The ratio of emergy fed back from outside a system to the indigenous emergy inputs (both renewable and non-renewable). It evaluates if a process is a good user of the emergy that is invested, in comparison with alternatives.

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**Empower density.** The ratio of total emergy use in the economy of a region or nation to the total area of the region or nation. Renewable and nonrenewable emergy density are also calculated separately by dividing the total renewable emergy by area and the total nonrenewable emergy by area, respectively.
Several other ratios are sometimes calculated depending on the type and scale of the systems being evaluated...

Percent renewable emergy (\%Ren). The ratio of renewable emergy to total emergy use. In the long run, only processes with high \%Ren are sustainable.

Emergy exchange ratio. The ratio of emergy exchanged in a trade or purchase (what is received to what is given). The ratio is always expressed relative to one or the other trading partners and is a measure of the relative trade advantage of one partner over the other.

Units = sej/sej
**Emergy per capita.** The ratio of total emergy use in the economy of a region or nation to the total population. Emergy per capita can be used as a measure of potential, average standard of living of the population.