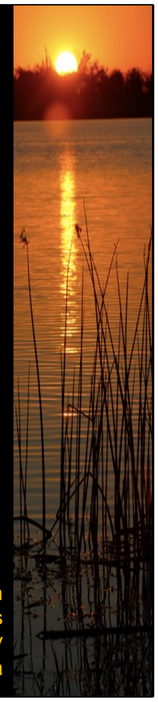
2026 International Summer Course on Environmental and Ecological System Engineering

Part A: Environmental Accounting and Systems Thinking (EAST)

Lecture 4:

Quantitative Emergy Evaluation



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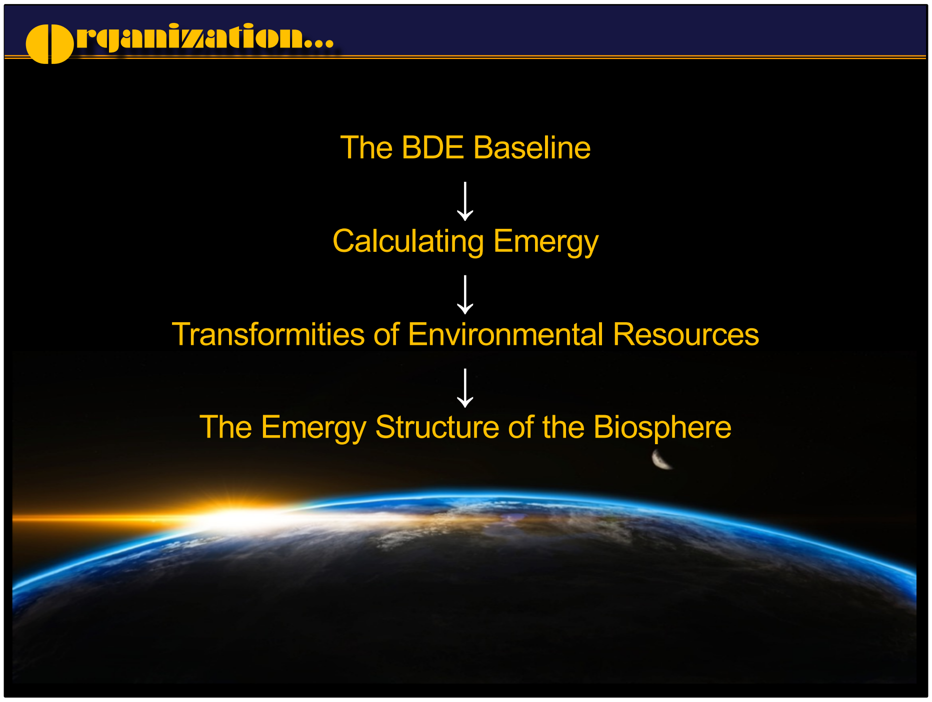
In this lecture we move from available energy to the quantitative calculation of emergy and transformity.

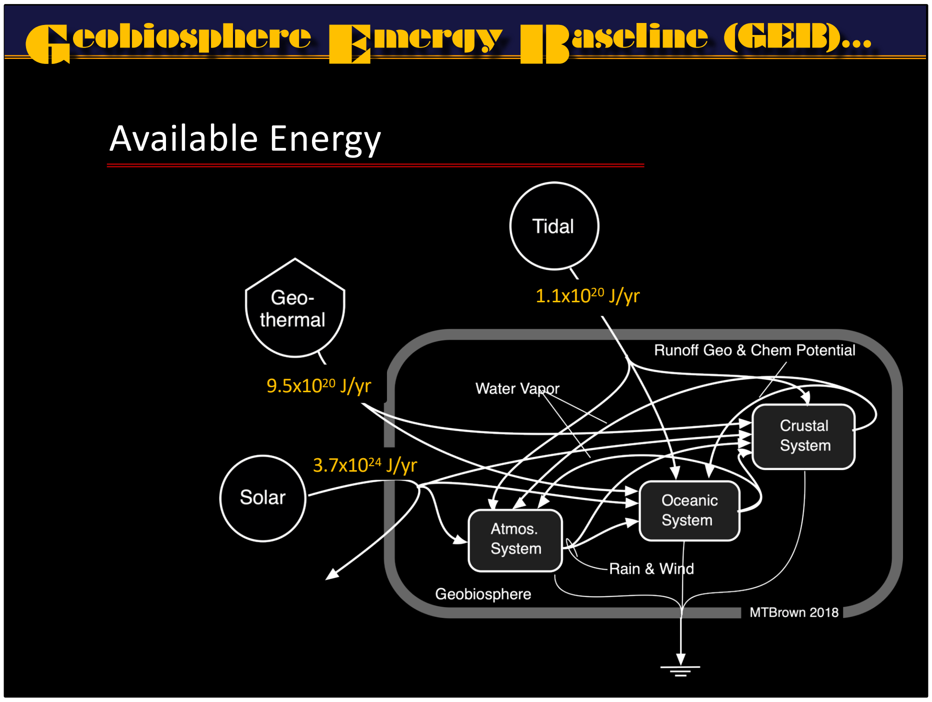


In the previous lecture we calculated the available energy contained in the major flows supporting the geobiosphere.

In this lecture we take the next step and convert those energy flows into emergy.

We begin by introducing the Biosphere Dynamic Empower baseline, then develop methods for calculating emergy and transformities.

Finally, we apply those methods to renewable resources, minerals, fossil fuels, and planetary systems, culminating in an emergy evaluation of the biosphere as a whole.



At the end of the previous lecture we identified the three primary energy sources supporting the geobiosphere: solar, tidal, and geothermal energy.

We also calculated their annual available energy flows.

To calculate emergy, however, we must first determine the transformity of each flow.

Geobiosphere Emergy Baseline (GEB)…

$$\text{Transformity} = \frac{\text{Emergy (sej)}}{\text{Energy (J)}}$$

$$\text{Emergy} = \text{Transformity} * \text{Energy}$$

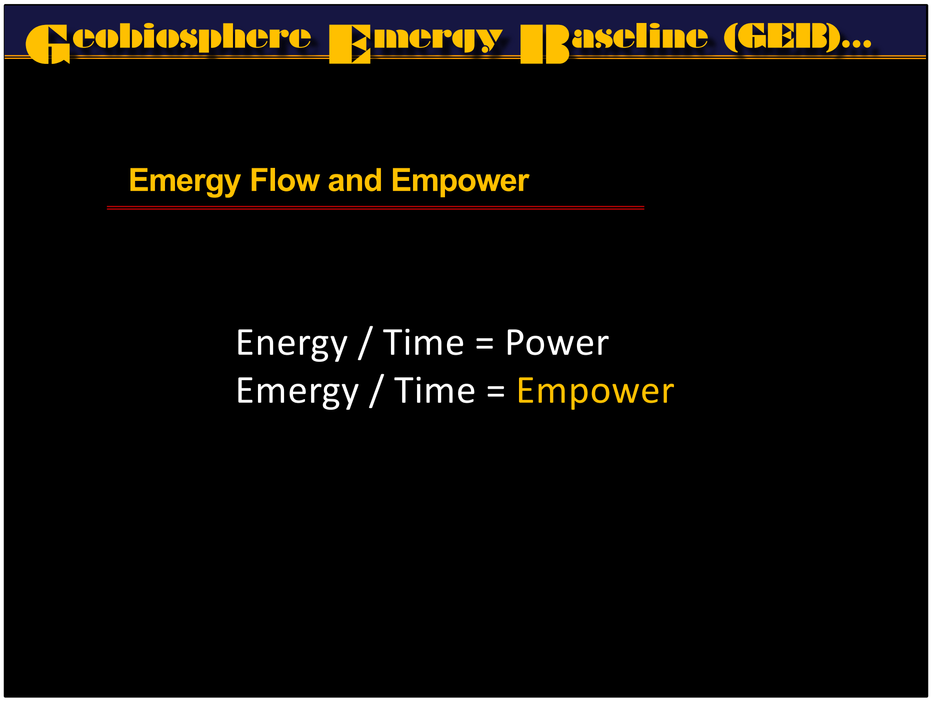
$$\text{sej} = \frac{\text{sej/J}}{\text{J}}$$

Recall for earlier lecture that Transformity is the ratio of emergy to available energy.

It represents the total amount of emergy required to generate one joule of available energy in a resource, product, or process.

The units of transformity are solar emjoules per joule, or sej/J.

The challenge is determining the transformities of the primary energy sources that drive the geobiosphere.



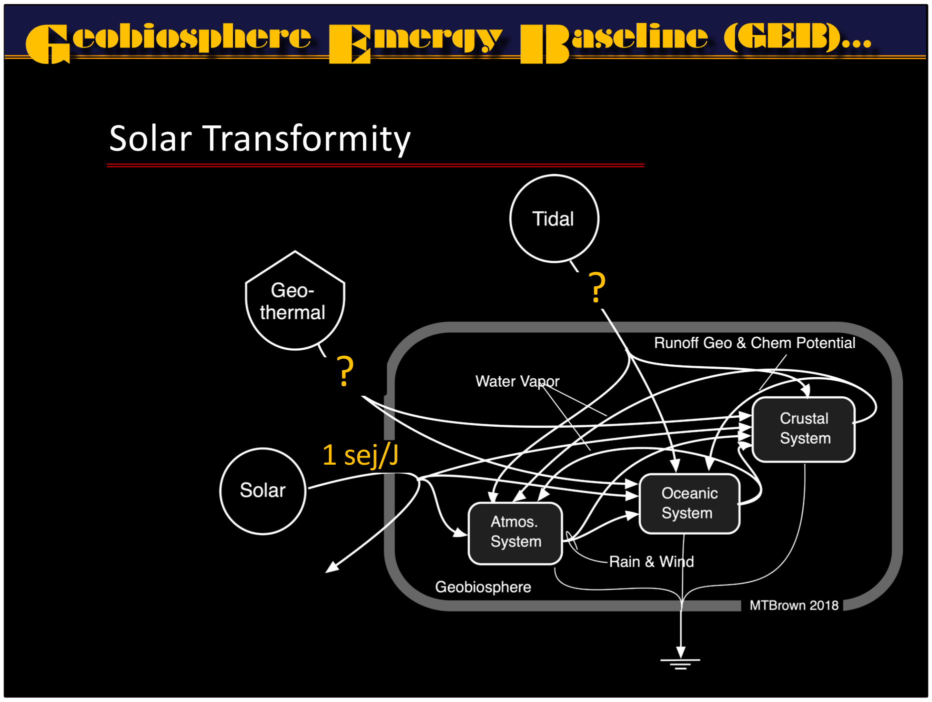
A BRIEF ASIDE>>>>

Just as power is the rate at which energy flows through a system, empower is the rate at which emergy flows through a system.

Power is measured in joules per unit time, while empower is measured in solar emjoules per unit time.

Because the geobiosphere and biosphere are continuously driven by energy flows, their emergy baselines are expressed as empower, measured in sej per year.

The Geobiosphere Empower and Biosphere Dynamic Empower therefore represent annual rates of emergy flow through the Earth system



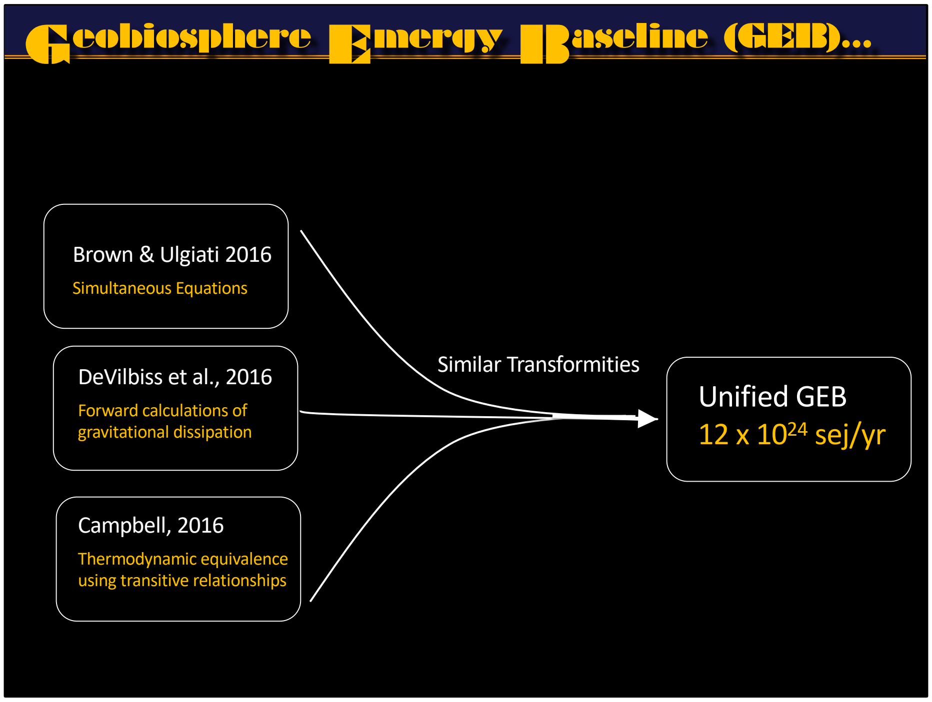
Solar radiation serves as the reference energy source for emergy accounting and is assigned a transformity of one solar emjoule per joule.

Determining the transformities of geothermal heat and tidal energy is more challenging.

Because these energy sources originate from different physical processes, their available energies cannot be directly expressed in equivalent emergy units.

The problem therefore becomes one of establishing an equivalence between solar energy, geothermal heat, and tidal energy so that all three can be placed on a common emergy basis.

Several independent methods were developed to estimate these equivalences.



Three independent research groups approached the problem using different methodologies.

Brown and Ulgiati used simultaneous equations and Monte Carlo simulation to account for uncertainty in the interactions among the three driving sources.

DeVilbiss and colleagues used a forward calculation of the dissipation of gravitational potential energy to establish equivalences among solar, geothermal, and tidal energy.

Campbell applied the transitive property of equalities to estimate thermodynamic equivalences between solar radiation, deep heat flow, and tidal dissipation.

Although based on different assumptions and methodologies, the three approaches produced remarkably similar estimates of tidal and geothermal transformities.

Mean values from the three studies were adopted to establish a unified geobiosphere baseline of approximately 12×10^{24} solar emjoules per year.

Geobiosphere Emergy Baseline (GEB)...

Inflow	Exergy	Transformity (sej/J)	Solar emergy (x 10^{24} sej/yr)
Solar energy absorbed	3.73E+24	1	3.73
Geothermal Flows	9.52E+20	4,900	4.73
Tidal energy absorbed	1.14E+20	30,900	3.54
Total Global Empower			12.0

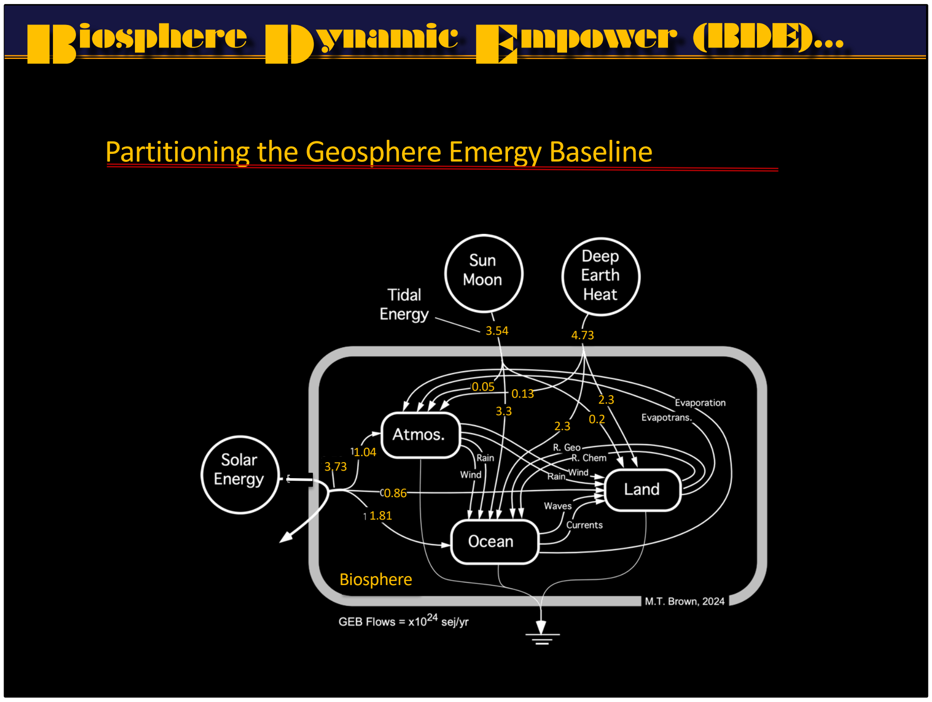
The transformities adopted from the three studies are shown here.

Solar radiation serves as the reference flow and is assigned a transformity of one solar emjoule per joule.

The transformities of geothermal heat and tidal energy express their equivalence relative to solar energy.

Multiplying the available energy of each source by its transformity yields its annual emergy contribution to the geobiosphere.

Summing these contributions gives a total geobiosphere baseline of 12 × 10^{24} solar emjoules per year.

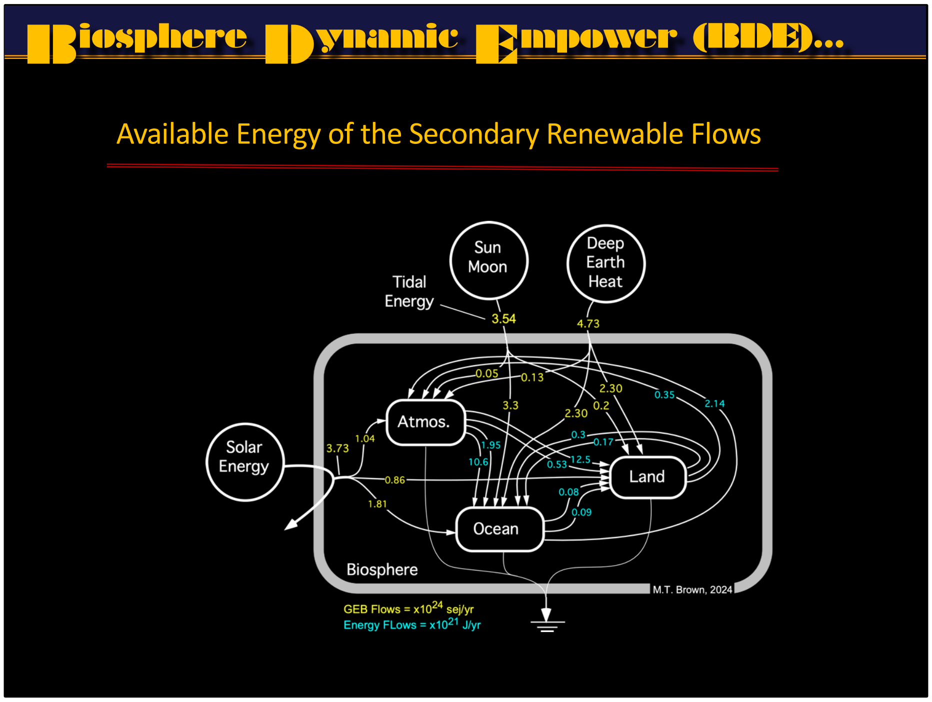


The geobiosphere baseline quantifies the emergy supplied by the Earth's primary driving sources.: solar radiation, geothermal heat, and tidal energy.

But many important renewable flows are not primary inputs. Wind, rain, river flow, waves, and ocean currents are generated within the biosphere.

These are secondary and tertiary renewable flows. Their emergy depends on the pathways of energy transformation that produce them.

To evaluate these flows, we first partition the geobiosphere baseline among the major compartments of the biosphere and then use matrix algebra to calculate the emergy of the internal flows.



The yellow values show the emergy assigned to the major biosphere components from the geobiosphere baseline, while the blue values show the available energy of the secondary and tertiary renewable flows.

Together these values define a network of interacting processes whose transformities can be determined simultaneously using matrix algebra.

These flows connect the atmosphere, oceans, and land through a network of interacting processes.

Because each flow both receives support from upstream processes and contributes support to downstream processes, their emergy cannot be determined independently.

Instead, the entire network must be solved simultaneously using matrix algebra.

Biosphere Dynamic Empower (BDE)…

From-to-matrix of energy flows and driving emergy used to compute dynamic transformities of biosphere secondary and tertiary renewable emergy

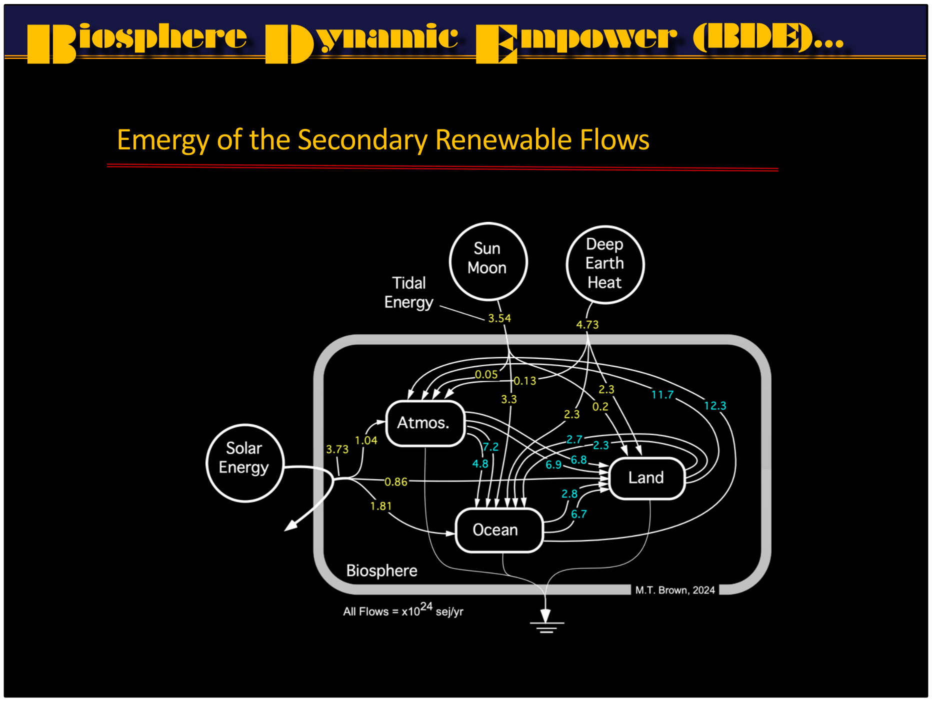
FROM / TO	Ocean Wind	Terrestrial Wind	Ocean Rain	Terrestrial Rain	Ocean Evaporation	Ocean Waves	Ocean Currents	Land Evapotrans.	River Chem. Pot.	River Geo. Pot.	**Emergy Vector**	**UEVs**
Ocean Wind	1.06E+22	0	0	0	-8.10E+20	0	0	0	0	0	1.06E+23	**450**
Terrestrial Wind	0	1.20E+22	0	0	0	0	0	-1.90E+20	0	0	7.08E+22	**540**
Ocean Rain	0	0	1.95E+21	0	-1.12E+21	0	0	0	0	0	7.79E+23	**3700**
Terrestrial Rain	0	0	0	5.2E+20	-2.10E+20	0	0	-1.6E+20	0	0	2.24E+23	**12900**
Ocean Evaporation	-3.32E+21	0	-1.365E+21	0	2.14E+21	0	0	0	-8.7E+18	0	5.60E+24	**5700**
Ocean Waves	-5.40E+21	0	0	0	0	7.57E+19	0	0	0	0	3.74E+23	**36800**
Ocean Currents	-1.88E+21	0	-5.85E+20	0	0	0	9.47E+19	0	-1.65E+20	0	1.49E+24	**70900**
Land Evapotranspiration	0	-1.21E+22	0	-1.78E+20	0	0	0	3.45E+20	0	0	2.85E+24	**33900**
River Chem. Potential	0	0	0	-1.77E+20	0	0	0	0	1.74E+20	0	6.70E+22	**13500**
River Geo. Potential	0	0	0	-1.77E+20	0	0	0	0	0	2.87E+20	4.36E+23	**9400**

The interactions among renewable flows are represented as a system of simultaneous equations.

The matrix coefficients describe the exchanges of energy among the flows, while the emergy vector contains the emergy assigned to each biosphere component.

Solving the matrix equation yields the transformities of the secondary and tertiary renewable flows.

Once the transformity of a flow is known, its emergy can be calculated by multiplying transformity by available energy.



The matrix solution allows the transformities of the secondary and tertiary renewable flows to be calculated.

Multiplying those transformities by their corresponding available energies yields the emergy of each flow.

The blue values show the emergy carried by the major renewable flows of the biosphere.

Notice that the emergy associated with these internal flows greatly exceeds the emergy assigned directly to the three primary driving sources.

This increase does not represent the creation of new energy. Rather, it reflects the repeated use and transformation of energy as it circulates through the atmosphere, oceans, and terrestrial systems.

Summing all of the renewable flows yields a Biosphere Dynamic Empower of approximately 40×10^{24} solar emjoules per year.

Biosphere Dynamic Empower (BDE)…

The BDE: emergy baseline for all minerals, fuels, and other nonrenewable sources

Available energy, dynamic transformities, and emergy of secondary and tertiary renewable sources

Component	Energy[1] ($\times 10^{21}$ J/yr)	D-Transformity[2] (sej/J)	Emergy[3] ($\times 10^{24}$ sej/yr)
Ocean Wind	10.6	450	4.8
Terrestrial Wind	12.50	540	6.8
Ocean Rain	1.95	3,700	7.2
Terrestrial Rain	0.53	12,900	6.9
Shore Waves	0.08	36,800	2.8
Ocean Currents	0.09	70,900	6.7
River Chemical Potential	0.17	13,500	2.3
River Geopotential	0.29	9,400	2.7
		Total	**40.0**

The results of the matrix evaluation are summarized in this table.

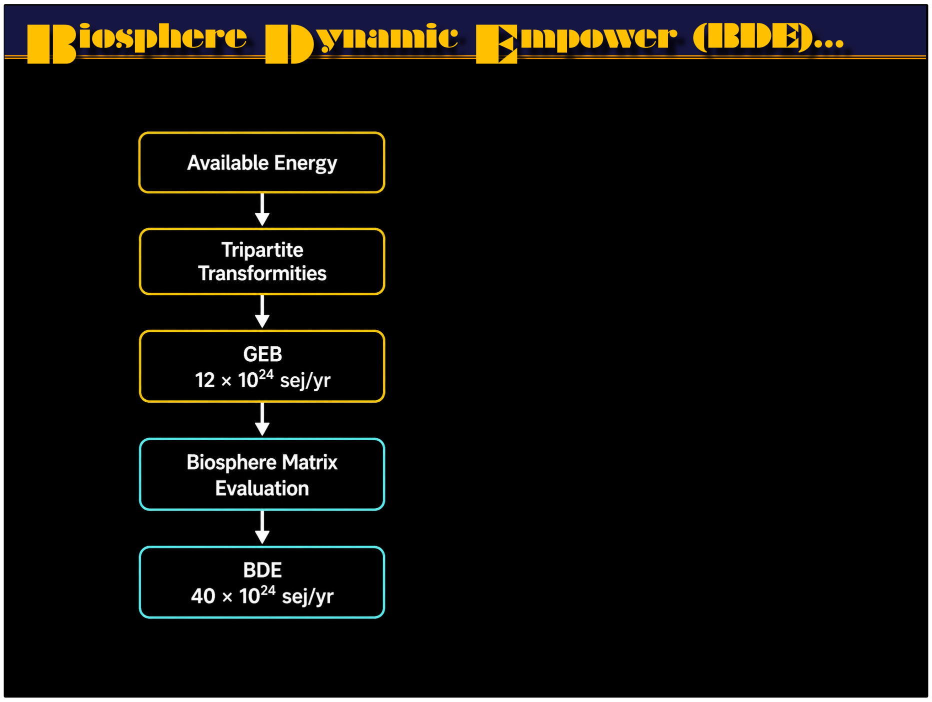
The first column lists the major secondary and tertiary renewable flows of the biosphere. The second column gives their annual available energy, while the third column gives the dynamic transformity calculated from the matrix solution.

Multiplying available energy by transformity yields the emergy of each flow shown in the final column.

Notice that the transformities increase as energy moves through successive stages of transformation. Ocean and terrestrial winds have relatively low transformities, while waves, river flows, and ocean currents have substantially higher values because they depend upon multiple preceding transformations.

Summing the emergy of all secondary and tertiary renewable flows yields approximately 40×10^{24} solar emjoules per year.

This quantity is the Biosphere Dynamic Empower, or BDE, and epresents the total emergy circulating through the renewable processes of the biosphere and serves as the emergy basis for evaluating minerals, fossil fuels, and other nonrenewable resources



Let's briefly review what we have accomplished.

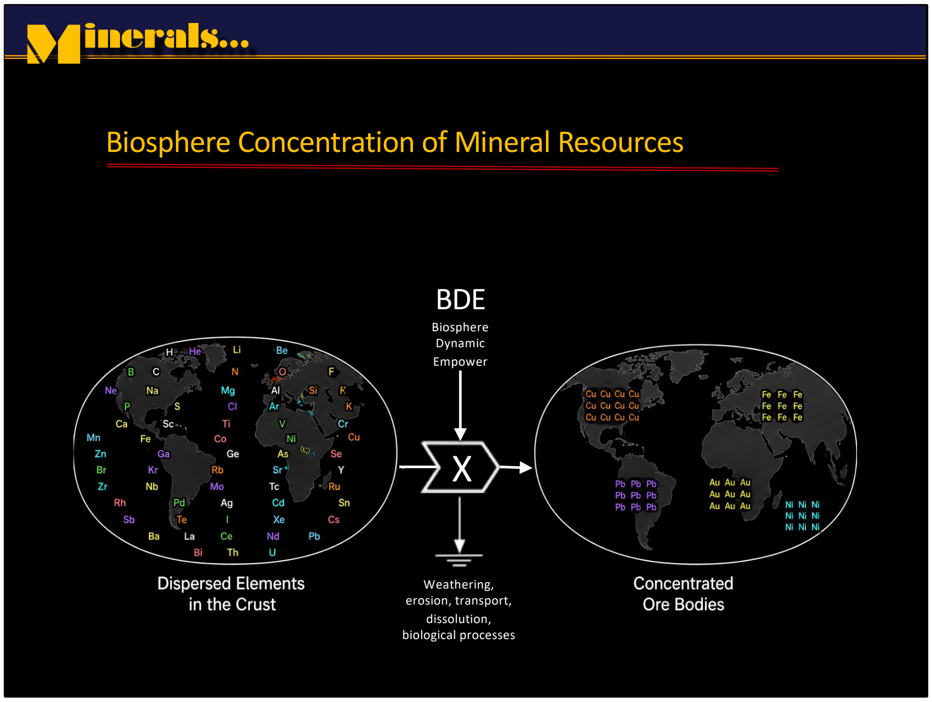
We began with the annual available energy supplied by the three primary driving sources of the Earth system: solar radiation, tidal energy, and geothermal heat.

By establishing equivalences among these sources, we determined their transformities and computed a geobiosphere baseline of 12×10^{24} solar emjoules per year.

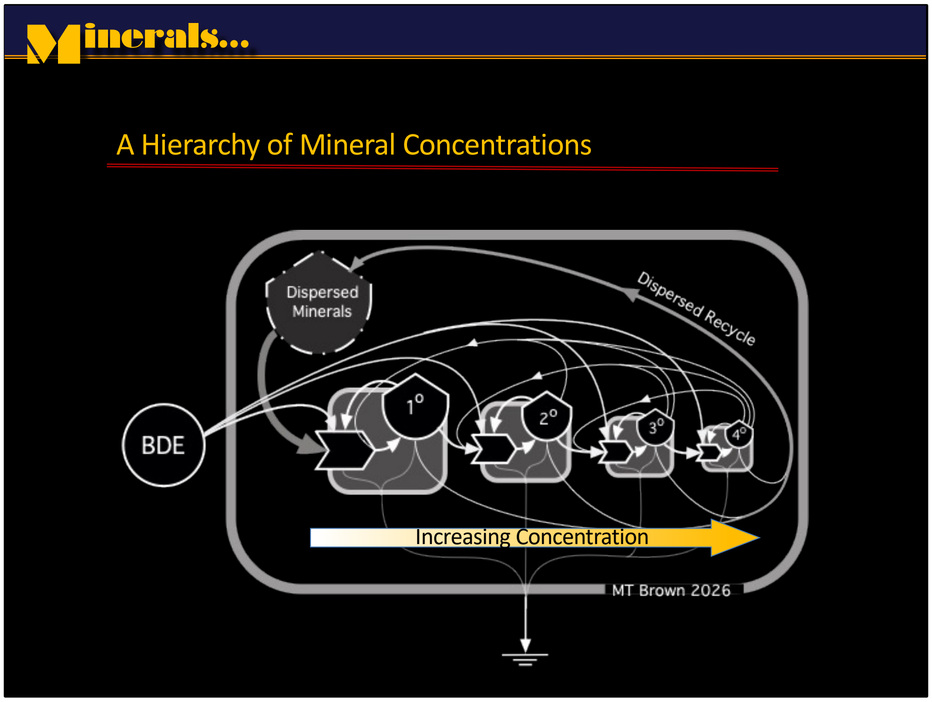
We then distributed this baseline among the major components of the biosphere and used matrix algebra to evaluate the transformities of the secondary and tertiary renewable flows.

The resulting emergy evaluation yielded a Biosphere Dynamic Empower of approximately 40×10^{24} solar emjoules per year.

We now have a quantitative emergy basis for evaluating minerals, fossil fuels, and other nonrenewable resources.



Most elements occur at low concentrations throughout the Earth's crust.
Over billions of years, physical, chemical, and biological processes continuously redistribute these materials.
Weathering breaks down rock, erosion transports material, rivers and groundwater move dissolved minerals, and biological activity alters chemical conditions.
Through repeated cycles of transformation and recycling, dispersed elements become concentrated into mineral deposits.
Because these concentration processes are driven by renewable flows within the biosphere, the Biosphere Dynamic Empower provides a basis for evaluating mineral resources.



Minerals become increasingly valuable as their concentration increases.
Higher concentrations require more work to overcome the natural tendency of matter to disperse.
As a result, the emergy embodied in a kilogram of mineral increases as ore grade increases.
Emergy analysis accounts for this concentration process by relating the concentration of a mineral deposit to the Biosphere Dynamic Empower that supports its formation.
In general, the rarer and more concentrated the deposit, the higher its unit emergy value.

Minerals...

UEVs of some common minerals and metal ores

Mineral	Mineral UEV [1] (x 10^9 sej/g)
Phosphate (as Apatite, 22% mineral)	6.29
Iron (as 25% FE)	9.91
Silver (0.00000042 g/g in gd)	13.1
Gold (0.00000043 g/g in gd)	13.8
Titanium (0.026 g/g in gd)	14.1
Uranium (as yellow cake; 80% UO_2)	14.5
Lead (concentrate, 0.03 g/g in gd.)	18.8
Limestone [4]	19.8
Bauxite (~ 40% alumina)	27.2
Copper (as $CuFeS_2$, 0.0142 g/g in gd)	44.8
Zinc (concentrate, 0.053 g/g in gd)	46.6
Lithium (as $LiAlSi_2O_6$; 0.0015 g/g in gd)	306.0

The UEVs of several common minerals are shown here.

These values represent the emergy embodied in one gram of mineral at the concentration at which it is mined.

Notice that minerals differ by more than an order of magnitude in their unit emergy values.

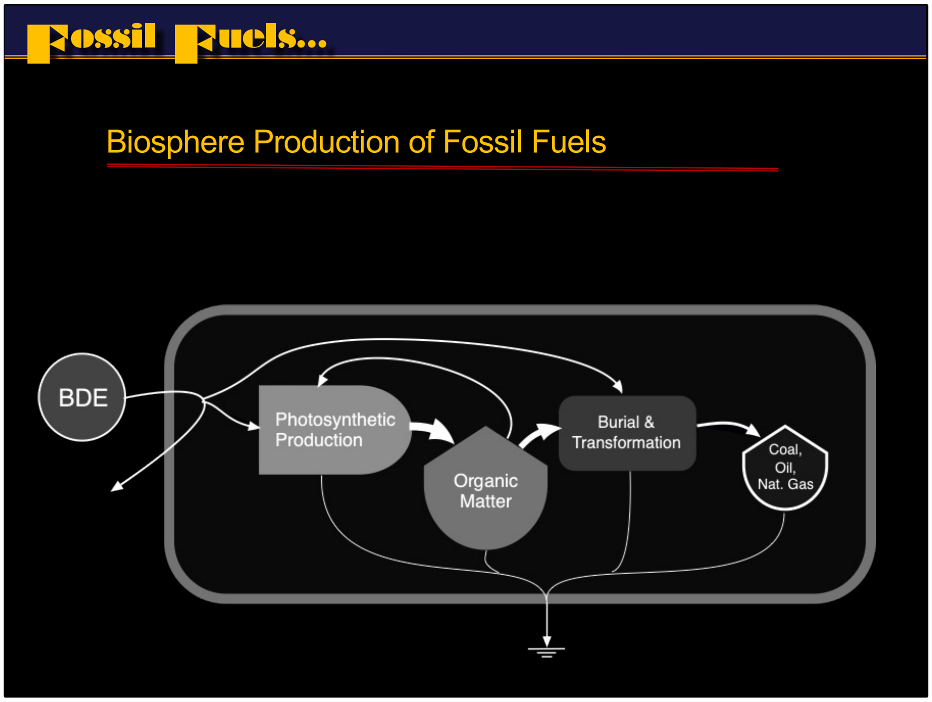
Common materials such as phosphate and iron have relatively low UEVs, while more concentrated or less abundant minerals such as copper, zinc, and lithium have much higher values.

These differences reflect the amount of biosphere work required to concentrate each mineral from its dispersed state in the Earth's crust.

In general, the rarer the mineral and the greater the concentration required to form an ore body, the higher its emergy value.

Lithium provides a useful example. Although only small quantities are mined, the natural processes required to concentrate lithium into mineable deposits are substantial, resulting in a very high unit emergy value.

Minerals represent concentrated stocks of matter. Fossil fuels represent concentrated stocks of chemical energy. We can apply the same emergy principles to evaluate their formation and concentration.



Fossil fuels originate from ancient organic matter produced by photosynthesis.

Only a small fraction of the organic matter produced each year escapes decomposition and becomes buried.

Over millions of years, heat, pressure, and geological processes transform this buried organic matter into coal, petroleum, and natural gas.

Because fossil fuels represent highly concentrated products of biosphere production, they possess high emergy values.

Fossil Fuels...

Oil and natural gas transformities across geologic ages

Geologic age	Oil (10^5sej/J)	NG (10^5sej/J)
Silurian	1.2	2.8
Upper Devonian-Turonian	2.6	6.0
Pennsylvanian-Lower Permian	1.2	2.8
Upper Jurassic	0.3	0.8
Middle Cretaceous	2.6	1.3
Oligocene-Miocene	1.2	1.7
Weighted Average	**1.54**	**1.92**

Oil and natural gas formed in different geologic periods have somewhat different transformities, reflecting differences in the conditions under which the original organic matter was produced, buried, and transformed.

Despite this variation, the weighted averages are relatively consistent, yielding transformities of approximately 1.5×10^5 sej/J for petroleum and 1.9×10^5 sej/J for natural gas.

These values are substantially higher than those of most renewable energy flows because fossil fuels represent highly concentrated stores of ancient biosphere production.

Fossil Fuels...

Transformities of hard and soft coal by geologic period

Period	% of Coal Resource	Anthracite & Bituminous (sej/J)	Sub-bituminous & Lignite (sej/J)
Devonian	0.1%	3.53E+05	2.74E+05
Carboniferous	24.3%	2.14E+05	1.66E+05
Permian	31.7%	2.16E+04	1.67E+04
Triassic	0.4%	2.43E+05	1.88E+05
Jurassic	16.8%	8.14E+04	6.32E+04
Cretaceous	13.3%	8.65E+04	6.72E+04
Tertiary	13.5%	1.05E+05	8.15E+04
Weighted Average		**9.95E+04**	**7.72E+04**

Coal transformities also vary among geologic periods and coal types.

In general, higher-rank coals such as anthracite and bituminous coal have larger transformities than lower-rank coals such as lignite.

This reflects the additional geological work required to transform organic matter into more concentrated forms of chemical energy.

Although individual deposits differ, the weighted average transformities are approximately 1×10^5 sej/J for hard coals and 8×10^4 sej/J for soft coals.

Fossil Fuels...

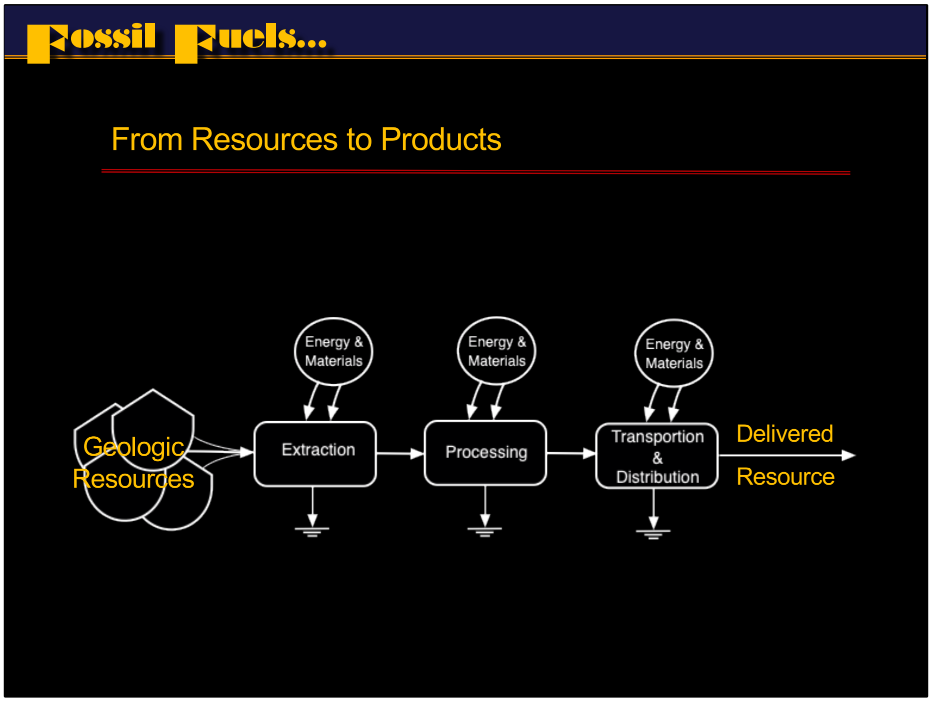
Fossil Fuels as Concentrated Biosphere Production

Resource	Transformity (sej/J)
Soft Coal	77,200
Hard Coal	99,500
Oil	154,000
Natural Gas	193,000

Fossil fuels have transformities that are one to two orders of magnitude greater than most renewable flows.

They represent highly concentrated stores of chemical energy produced by the biosphere and preserved over geologic time.

Because their formation requires large amounts of biosphere production and long periods of burial and transformation, fossil fuels embody substantial emergy.



The UEVs calculated in this lecture represent geologic resources as they occur in the environment.

For minerals, the values represent the emergy required to concentrate dispersed elements into mineable ore bodies.

For fossil fuels, the values represent the emergy required to produce and concentrate coal, petroleum, and natural gas within the Earth.

However, these resource UEVs do not include the additional emergy required for exploration, extraction, processing, transportation, manufacturing, and delivery.

Each of these activities requires energy, materials, labor, and infrastructure, adding further emergy to the final product.

As a result, the UEV of a resource at the point of end use is often substantially greater than the UEV of the natural resource itself.

In later lectures we will extend these evaluations to include the full production system and calculate UEVs for products, services, and economic processes.

Global Economy…

Flux of renewable and non-renewable energies driving global processes (2022)

Source	Emergy (10^{24} sej yr^{-1})	Percent of Total
Global Renewable Energies		
Terrestrial BDE	18.7	
Marine BDE	21.5	
Renewable Subtotal	40.2	13.5%
Society Released Energies (non-renewables)		
Oil	27.9	
Natural gas	26.1	
Soft Coal	4.1	
Hard Coal	15. 7	
Soil erosion	23.3	
Nonrenewable subtotal	74.0	24.8%
Minerals and Metals		
Non-metal minerals	142.8	47.8%
Metals	41.6	13.9%
TOTAL	**298.61**	

This table summarizes the annual emergy flows evaluated in this lecture.

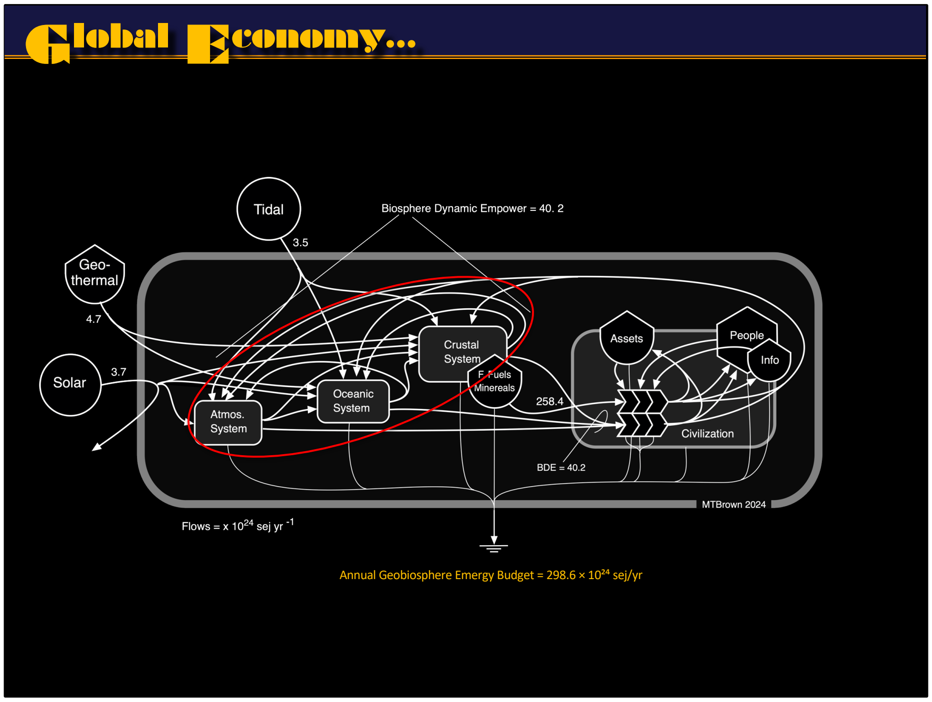
Renewable flows account for approximately **14%** of the total emergy evaluated, representing the continuous support provided by the biosphere.

Nonrenewable resources, including fossil fuels and soil erosion, contribute about **25%** of the total.

The largest contribution, nearly **48%**, comes from non-metal minerals, primarily by limestone extraction for cement and concrete production. Although limestone has a relatively modest unit emergy value, the quantities used by human society are enormous.

These results demonstrate that both the quality of a resource and the quantity utilized influence its total emergy contribution.

Together, these flows provide a quantitative picture of the environmental work supporting human activities and the resources on which modern civilization depends.



Let us conclude by stepping back and looking at the Earth system as a whole.

The three primary energy sources—solar radiation, tidal energy, and geothermal heat—drive the atmosphere, oceans, and crustal systems of the geobiosphere.

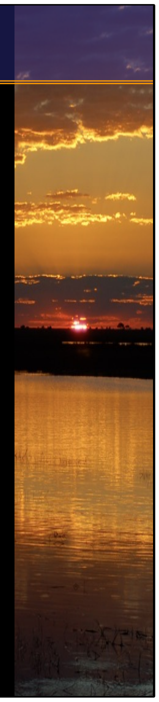
These processes generate the Biosphere Dynamic Empower and support the formation of renewable resources, mineral deposits, and fossil fuels.

Human civilization depends upon these flows and accumulated stocks of emergy. Assets, information, and human activities are ultimately supported by the environmental work embodied in these resources.

The annual geobiosphere emergy budget evaluated in this lecture is approximately 3×10^{26} solar emjoules per year.

In the next lecture, we will extend this analysis from planetary resources to the emergy evaluation of economies, regions, and nations.

Thank You...



Thank You for Your Attention

感谢您的聆听