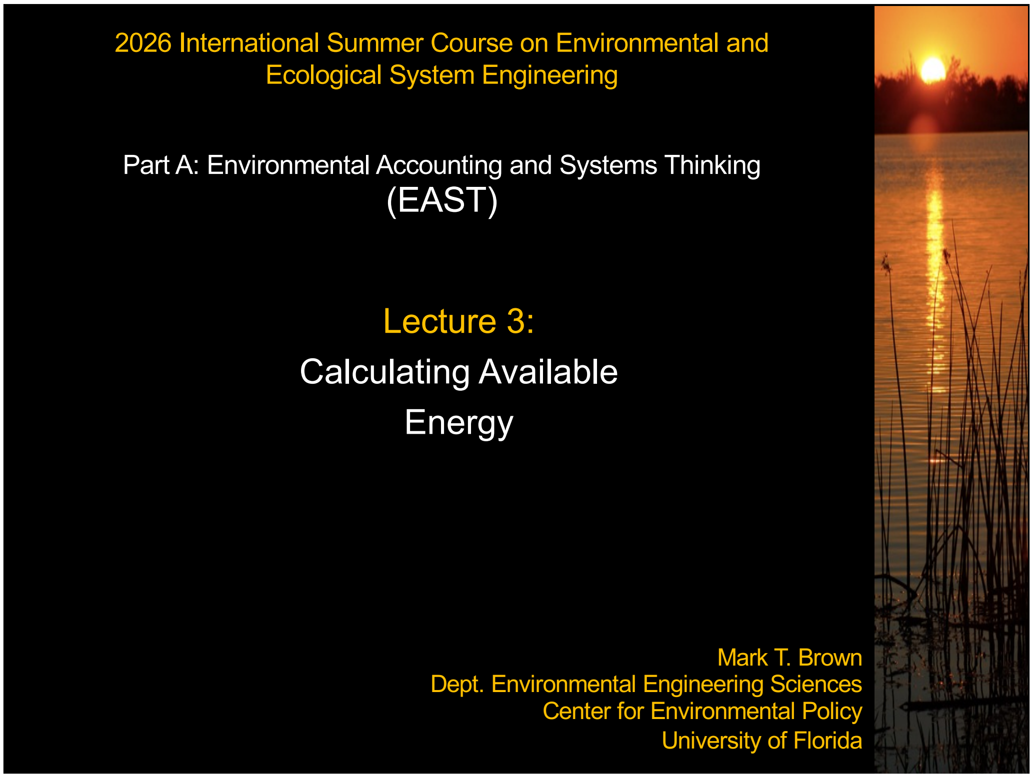
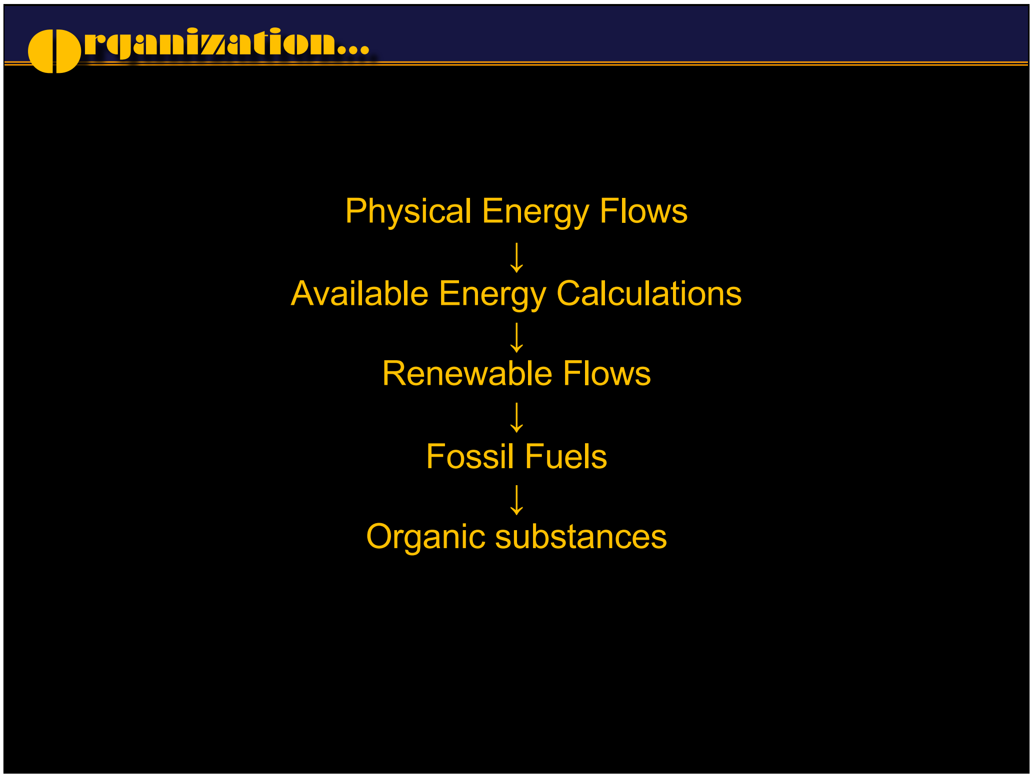


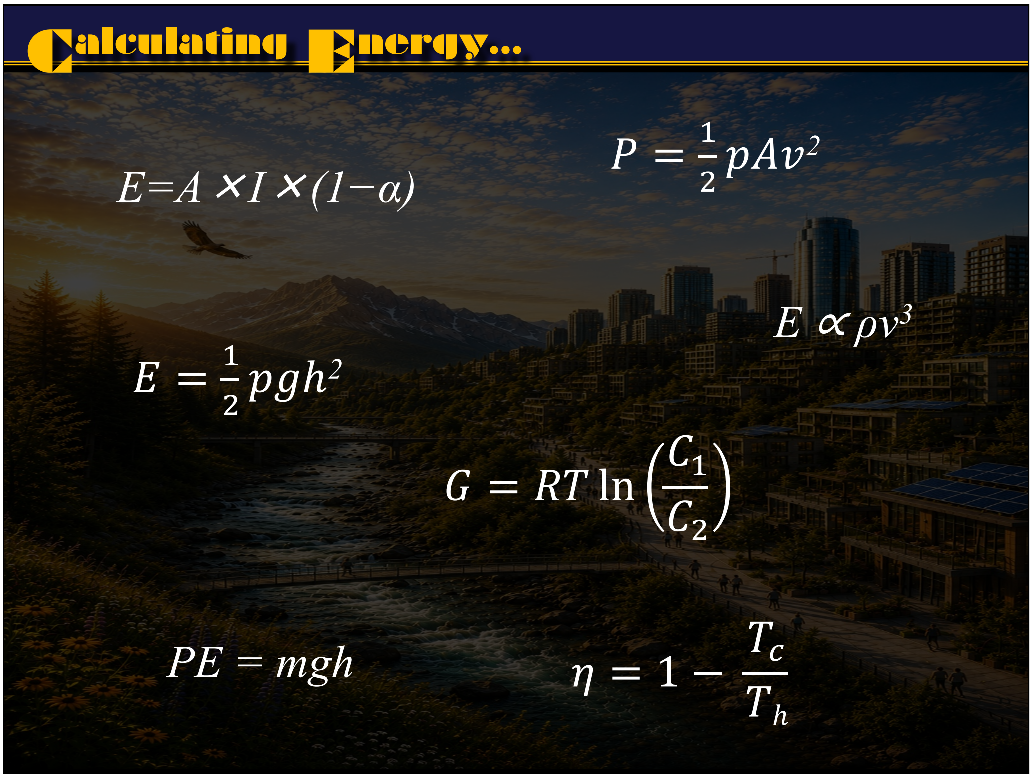
In this lecture we develop the practical calculations of available energy of resources.



Before we can calculate emergy, we must first calculate the available energy contained in environmental resources.

In this lecture we will examine several common renewable energy flows and see how thermodynamics is used to quantify their available energy.

These calculations provide the foundation for emergy analysis.



We begin by considering the major environmental energy flows that support the geobiosphere.

Sunlight, wind, rainfall, river flow, tides, waves, and geothermal heat all contain available energy that can be quantified using physical laws.

The equations shown on this slide may look very different, but they all serve the same purpose: they estimate the available energy contained in environmental resources.

Once available energy has been calculated, emergy is obtained by multiplying by the appropriate Unit Emergy Value.

In the remainder of this lecture we will examine several of these calculations and see how thermodynamics provides the foundation for emergy accounting.

Calculating Energy...

Computing Available Energy ...

Renewable Sources	Available Energy Form
Sunlight	Radiant
Wind	Kinetic
Rain	Chemical Potential
River	Chemical & Geopotential Energy
Ocean Waves	Kinetic & Potential
Tide	Gravitational Potential
Geothermal	Thermal Gradient

The first step in emergy evaluation is to quantify the available energy contained in environmental resources.

Not all resources store energy in the same form.

Sunlight carries radiant energy. Wind contains kinetic energy associated with moving air masses. Rainfall and river water contain chemical potential energy associated with the concentration difference between fresh water and seawater.

Water moving across the landscape also contains gravitational, or geopotential, energy. Tides derive from gravitational interactions among the Earth, Moon, and Sun, while ocean waves contain both kinetic and potential energy. Geothermal resources represent energy stored in thermal gradients within the Earth.

Because each resource stores energy differently, there is no single equation for available energy. Instead, we select the thermodynamic relationship appropriate for each resource.

In the following slides, we will examine several of these calculations and see how they provide the foundation for emergy accounting.

Energy of Renewable Sources…

Sunlight

$$E = A\,S\,(1 - albedo)t$$

where:

A = area
S = average solar radiation at surface
albedo = reflected fraction
t = time, seconds

Solar Insolation varies with latitude…

Gainesville ~ 150 Cal /cm^2 /y^r

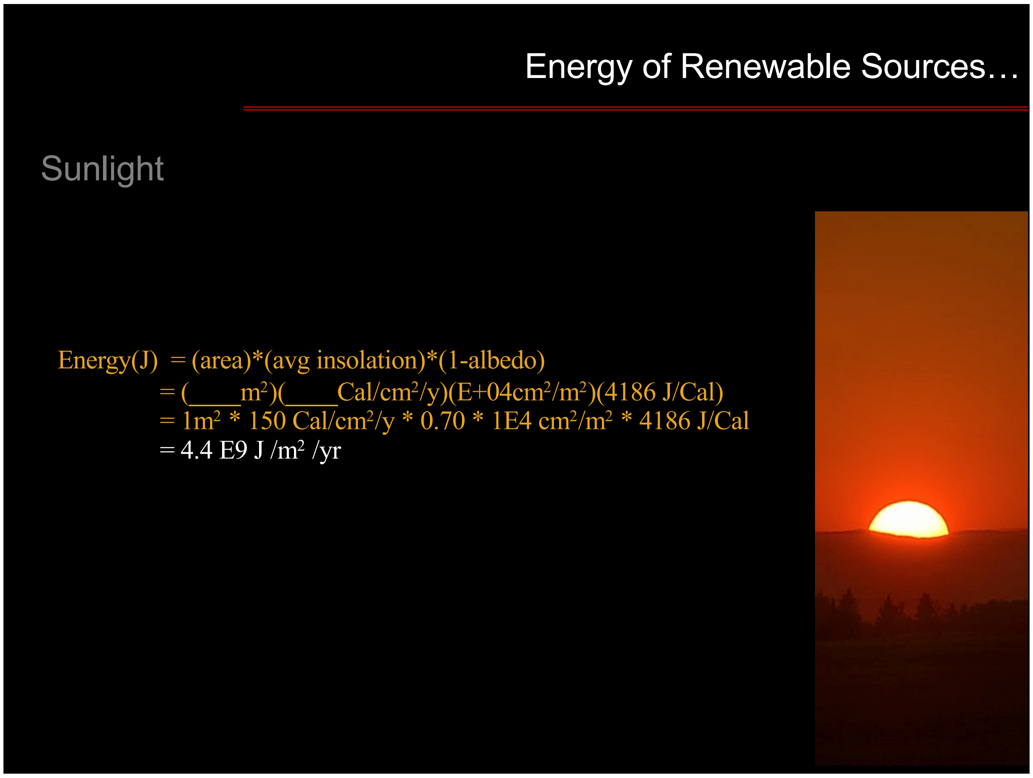
Global average albedo = 30%

We begin with the largest energy input to the Earth system: solar radiation.

The amount of solar energy received at a location depends on the incoming solar radiation, the area being considered, and the fraction reflected back to the atmosphere and space.

This reflected fraction is known as albedo

The average overall albedo of Earth, its *planetary albedo*, is 30%, but varies widely due to local conditions across the surface,



In this example, using average conditions for Gainesville, Florida (My home town), the average annual solar insolation is approximately 150 calories per square centimeter per year.

After accounting for the Earth's average albedo of about 30 percent, the absorbed solar energy is approximately 4.4×10^9 joules per square meter per year.

Similar calculations can be performed for any location using local measurements of solar radiation.

Solar energy is particularly important because it drives most renewable processes on Earth, including atmospheric circulation, the hydrologic cycle, and photosynthesis. For this reason, many of the energy flows examined in the following slides can ultimately be traced back to solar radiation.

Energy of Renewable Sources…

Kinetic Energy of Wind

$$E = \frac{1}{2}\rho A C_d \left(v_g^3 - v_s^3\right) t$$

where:

- E = energy, J
- ρ = air density, kg/m³
- A = area, m²
- C_d = drag coefficient
- v_g = geostrophic wind speed, m/s
- v_s = surface wind speed
- t = time, seconds

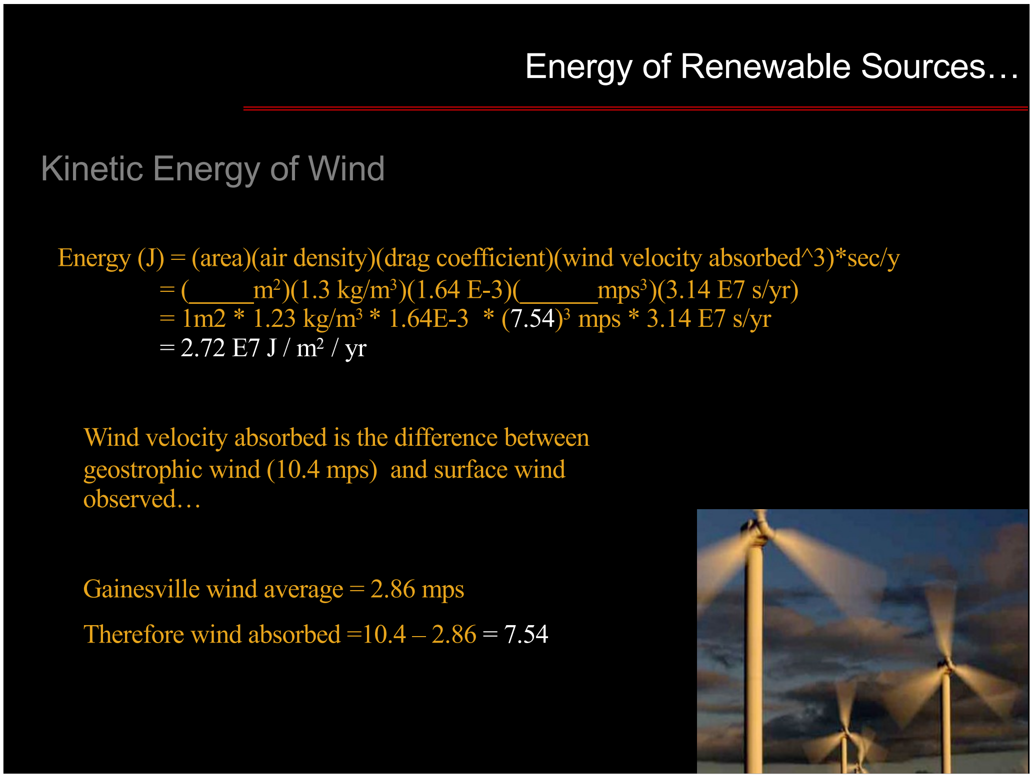
Wind contains kinetic energy associated with moving air masses.

In emergy analysis we are interested in the portion of atmospheric motion that is transferred to the Earth's surface through friction and turbulence.

The equation shown here estimates that energy transfer using air density, surface drag, and wind velocity.

Notice that wind velocity is raised to the third power.

The cubic relationship between wind speed and energy is why windy locations contain disproportionately larger amounts of available energy.



In this example, the absorbed wind velocity is estimated as the difference between geostrophic wind speed and the observed surface wind speed.

Using representative values for Gainesville, the resulting available wind energy is approximately 2.7×10^7 joules per square meter per year.

Although wind contains far less energy than sunlight, it plays a critical role in redistributing solar energy throughout the atmosphere and driving weather and climate.

Energy of Renewable Sources…

Chemical Potential Energy in Rain

First: Gibbs free energy in water.

Gibbs free energy for 10ppm rain relative to seawater salinity in evapotranspiring plants or to estuaries receiving fresh water…

$$G = \frac{RT}{w} ln\left(\frac{C_2}{C_1}\right)$$

$$G = \frac{\frac{8.314J}{mole}/287.25°K}{18\ g/m\,ole}\ \ ln\left(\frac{999{,}990\ ppm}{965{,}000\ ppm}\right)$$

$$G = 4.74\ J/g$$

The hydrologic cycle continuously separates pure water from dissolved salts. As seawater evaporates, the salts are left behind, producing fresh water that later returns to the Earth as rainfall.

This separation creates a concentration difference between fresh water and seawater. Whenever a concentration difference exists, there is a potential for mixing, and therefore a potential to perform work.

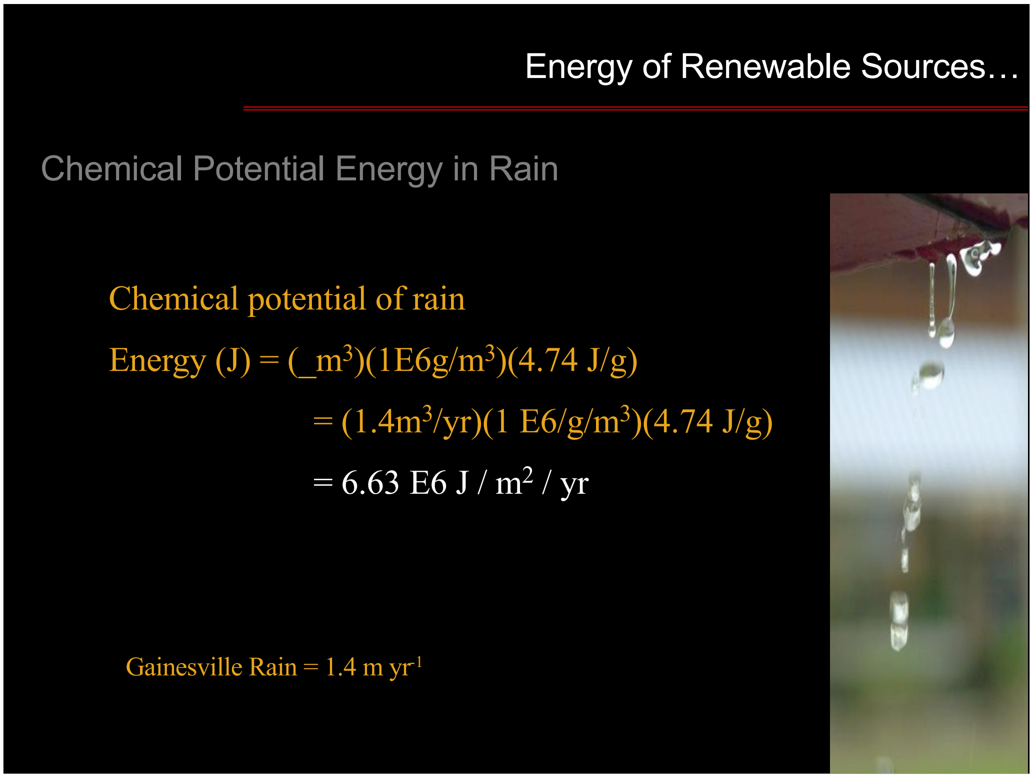
The Gibbs free energy equation shown here allows us to quantify that potential. Using a typical rainwater salinity of about 10 parts per million and comparing it to seawater, we calculate a chemical potential of approximately 4.74 joules per gram of fresh water.

This value represents the maximum useful energy available when fresh water mixes with seawater.

This concentration gradient is important not only in rivers and estuaries. Living cells also maintain internal salt concentrations that differ from their surroundings.

Organisms use these gradients to regulate water balance, transport nutrients, remove wastes, and maintain cellular organization.

Thus, the chemical potential of rainfall is more than a property of water chemistry. It is one of the renewable environmental energy flows that helps support both ecosystems and living systems.



On the previous slide, we calculated that each gram of fresh rainwater contains approximately 4.74 joules of chemical potential energy relative to seawater.

We can now estimate the total available energy delivered by rainfall to a unit area of land.

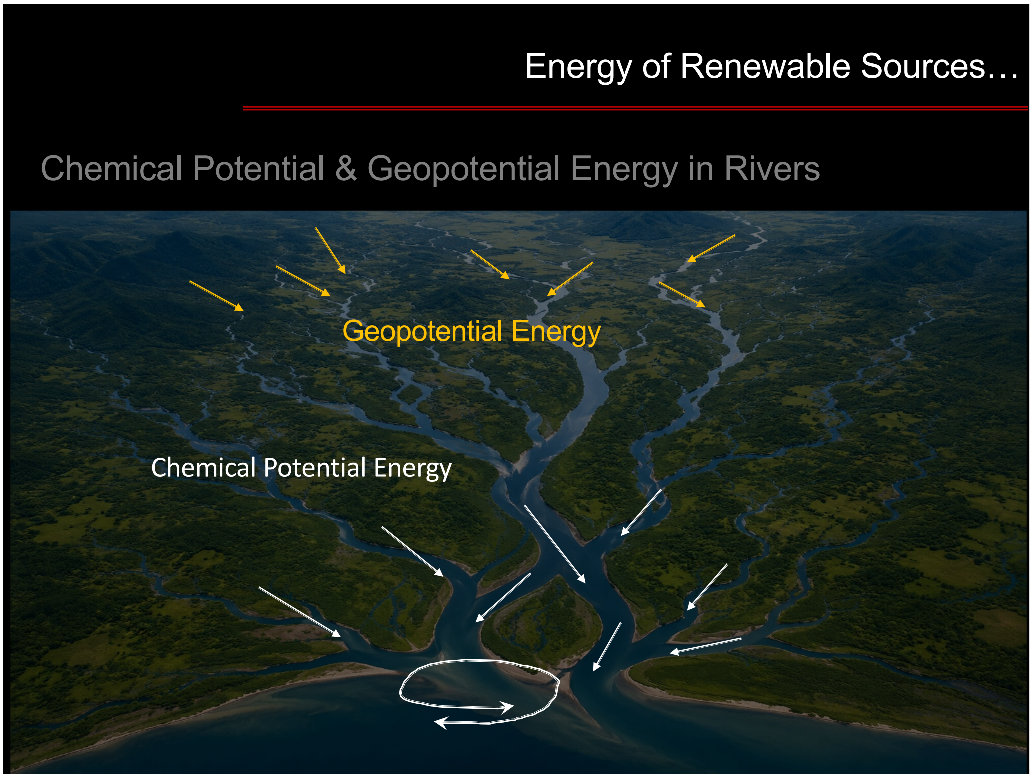
In Gainesville, Florida, average annual rainfall is about 1.4 meters per year. Over one square meter of land, this corresponds to 1.4 cubic meters of water, or about 1.4 million grams of rainwater.

Multiplying the mass of rainfall by the Gibbs free energy of 4.74 joules per gram yields approximately 6.6×10^6 joules of chemical potential energy per square meter per year.

This value represents the renewable energy supplied by the hydrologic cycle through the continual production of fresh water.

Notice that we are not calculating the kinetic energy of falling raindrops. Instead, we are calculating the energy stored in the concentration difference between fresh water and seawater—a gradient created and maintained by solar energy driving evaporation and condensation.

This chemical potential energy becomes available whenever fresh water enters soils, ecosystems, rivers, estuaries, and ultimately the ocean.

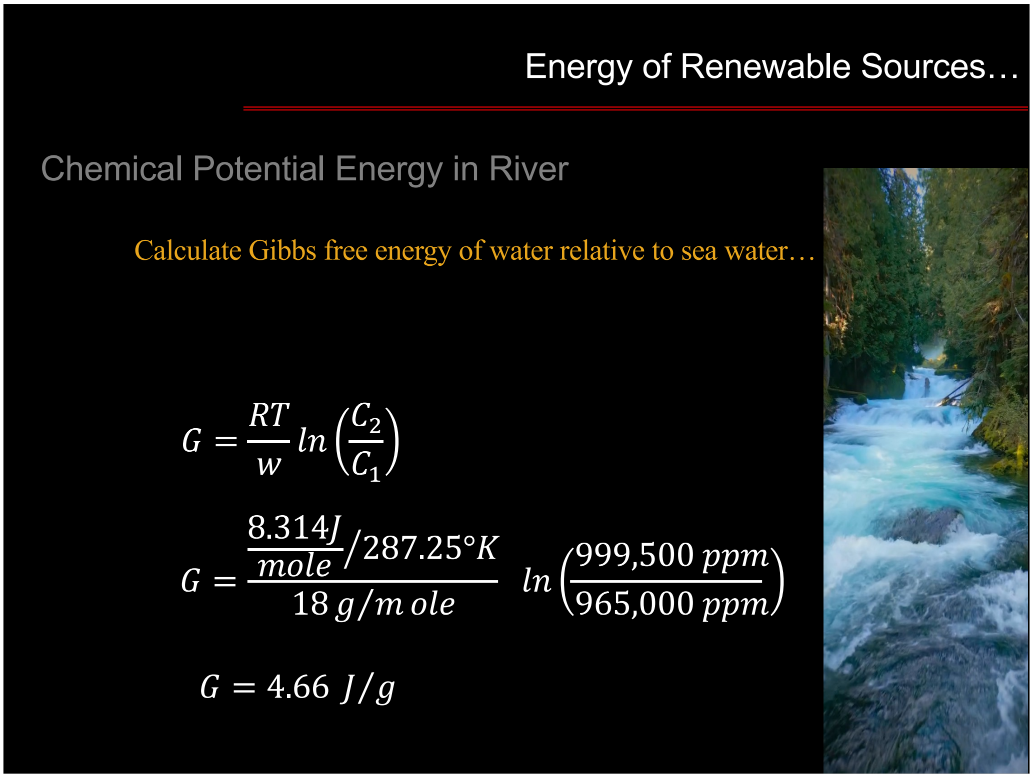


River systems contain two distinct forms of available energy.

The first is chemical potential energy associated with the salinity difference between fresh water and seawater.

The second is geopotential energy resulting from water flowing downhill under gravity.

Both contribute to the total available energy of river systems.



River water contains dissolved minerals and salts, so its chemical potential is slightly lower than that of rainfall.

In this example we assume a dissolved solids concentration of about 500 parts per million.

Using the same Gibbs free energy equation, we calculate the available chemical potential of river water relative to seawater.

The result is approximately 4.66 joules per gram, only slightly lower than the value obtained for rainfall.

Energy of Renewable Sources…

Chemical Potential Energy in River

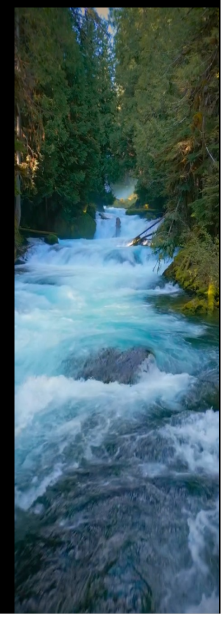
Chemical potential of river discharge

$$\text{Energy (J)} = (\_\text{m}^3)(1\text{E6g/m}^3)(\text{Gibbs J/g})$$

$$= (1.0 \text{ m}^3 \text{ yr}^{-1})(1 \text{ E6 g m}^{-3})(4.66 \text{ J g-}^{1})$$

$$= 4.66 \text{ E6 J / m}^3$$

Assume 500 ppm dissolved solids... therefore G = 4.66

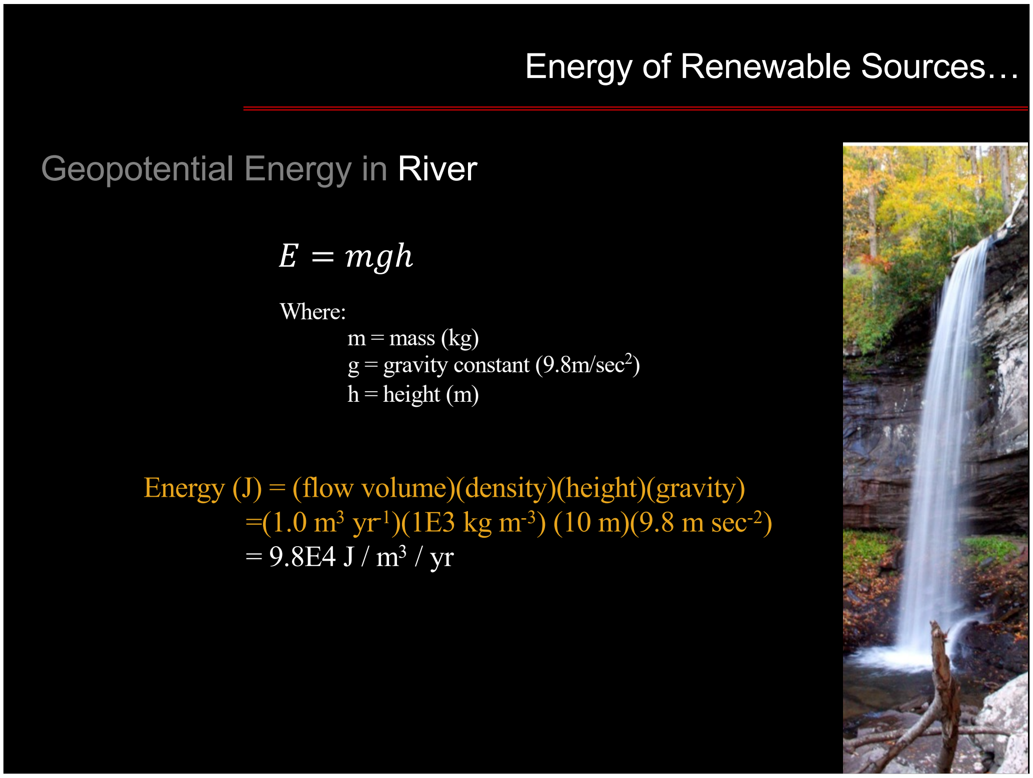


We now convert the Gibbs free energy value into available energy per unit volume of river discharge.

Multiplying the Gibbs free energy by the mass of water in one cubic meter gives approximately 4.7 million joules of chemical potential energy per cubic meter of river water.

This energy becomes available when fresh water mixes with seawater in estuaries and coastal environments.

Notice that this chemical potential is much larger than the geopotential energy we will calculate next.



River water also contains gravitational, or geopotential, energy because it is elevated above sea level.

The calculation is simply the familiar expression mass time gravity times height (mgh).

In this example, one cubic meter of water descending ten meters contains about ninety-eight thousand joules of available energy.

Compared with the chemical potential energy associated with freshwater mixing, the geopotential component is relatively small.

Nevertheless, it is the component that humans most often capture through hydroelectric generation.

Energy of Renewable Sources…

Waves Absorbed at the Shore

$$E = L\left(\frac{1}{8}\rho g H^2\right)C$$

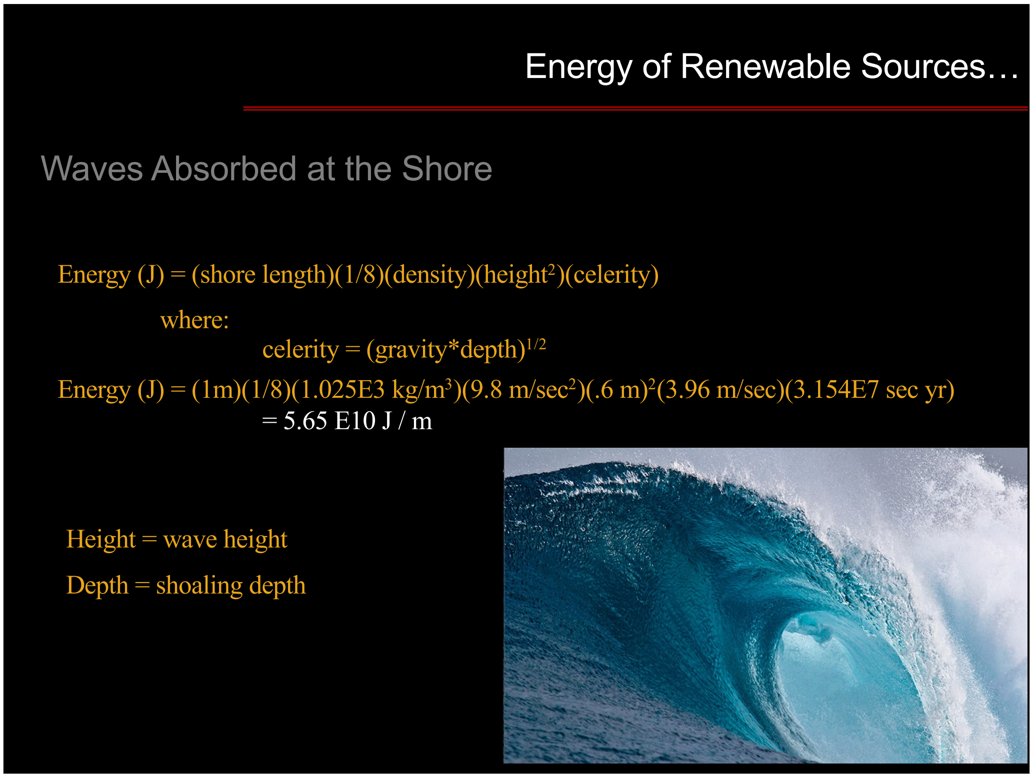
Where:

- E = wave energy (J/m)
- ρ = density of sea water (1.025 kg/m^3)
- g = gravity (9.8 m/s^2)
- H = wave height (m)
- d = shoaling depth
- C = $\sqrt{gd}$ shallow-water wave celerity

Ocean waves contain both potential energy associated with wave height and kinetic energy associated with water motion.

As waves move into shallow water and break along shorelines, this energy is dissipated and becomes available to coastal ecosystems.

The equation shown here estimates the rate at which wave energy is delivered to a shoreline.



This example estimates the annual wave energy absorbed along one meter of shoreline.

The calculation depends primarily on wave height and water depth, which determine the speed at which wave energy approaches the coast.

Using representative values, the result is approximately 5.7×10^{10} joules per meter of shoreline per year.

This is a remarkably large energy flow and helps explain why coastlines are among the most dynamic environments on Earth.

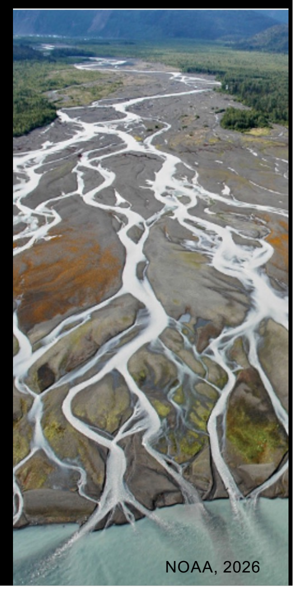
Energy of Renewable Sources…

Tide Absorbed in Estuaries

$$E = \frac{1}{2}\, A\, pgh^2\, N$$

Where:

- A = estuary surface area
- *ρ = density of seawater*
- *g = gravity*
- *h = tidal height*
- *N = number of tides per year*



NOAA, 2026

Tidal energy becomes available when seawater moves into and out of estuaries during each tidal cycle.

As water flows through channels, across tidal flats, and around marshes and wetlands, energy is dissipated through friction and turbulence.

The equation shown here estimates the rate at which tidal energy is absorbed within estuaries. The calculation depends on tidal range, estuary area, seawater density, gravitational acceleration, and the number of tidal cycles each year.

In emergy analysis, this dissipated energy represents the available energy supporting estuarine ecosystems.

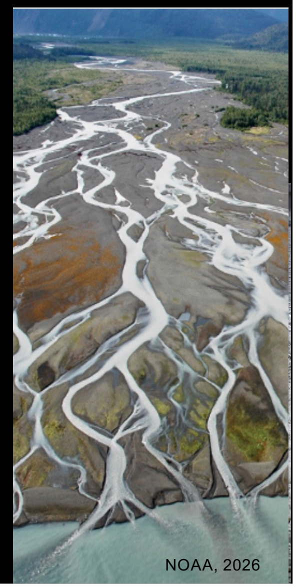
Energy of Renewable Sources…

Tide Absorbed in Estuaries

Energy (J) = (area)((0.5)(tides/yr)(height^2)(density)(gravity)

= (1 m^2)(0.5)(706/yr)(0.8m^2)(1.025E3 kg/m^3)(9.8 m/sec^2)

= 2.27 E6 J /m^2 /yr



This example applies the tidal energy equation using representative values for estuary area and tidal range.

The result is approximately 2.3×10^6 joules per square meter per year of available tidal energy.

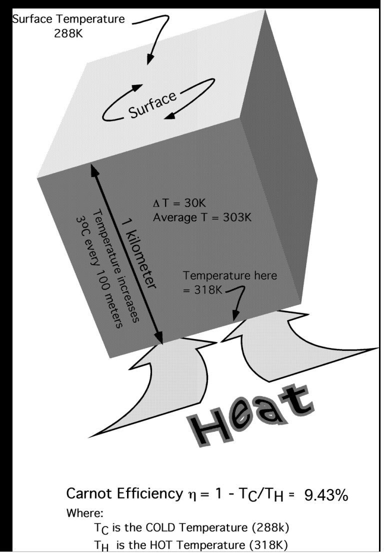
Through continual dissipation in channels, marshes, and estuaries, tidal energy contributes to the maintenance of highly productive coastal ecosystems.

Energy of Renewable Sources…

Geothermal energy

Calculation of geothermal exergy relies on computing a Carnot efficiency for the energy in the thermal gradient between the average temperature of the heat source and the average temperature of the reference environment.

Carnot Eff. = 1 - Tc / Th
= 1 – 288/318
= 9.43%



Only a fraction of thermal energy is available to do work. The Carnot efficiency estimates that fraction.

The greater the temperature difference between the heat source and its surroundings, the greater the available energy contained in the thermal gradient.

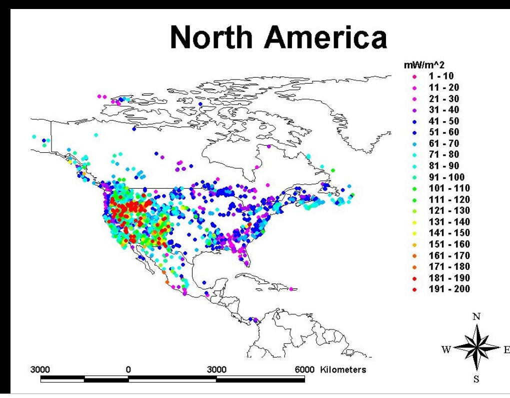
Energy of Renewable Sources…

Geothermal energy

$$E = \left(\frac{mW/m^2}{1,000}\right) x \frac{3.15E7s}{yr} x\, nc$$
$$= J/m^2/yr$$

Where:
- mW = milliwatts
- m^2 = area
- nc = carnot efficiency

Global Heat Flow Database



Once the Carnot efficiency has been calculated, it can be applied to the geothermal heat flux.

The Earth's crust continuously releases heat from its interior.

However, only the fraction represented by the Carnot efficiency is considered available energy.

Multiplying heat flow by time and Carnot efficiency converts total heat flow into geothermal available energy.

Energy of Renewable Sources…

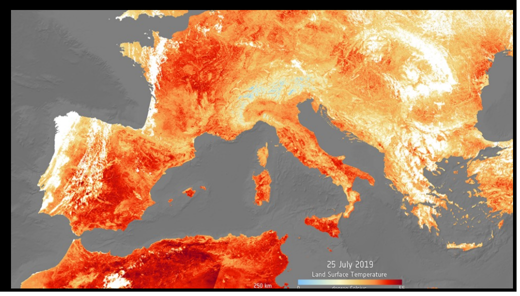
Geothermal energy

Mean crustal heat flow is 65 mW/m2 (2.05 E6 J/m^2/yr)

$$\text{Energy(J)} = \frac{(\text{mW}/\text{m}^2)}{1000} * 3.15\text{ E7 sec/yr} * \text{Carnot eff.}$$

$$= \frac{(65\text{ mW}/\text{m}^2)}{1000} * 3.15\text{ E7 sec/yr} * 9.43\%$$

$$= 1.93\text{ E5 J}/\text{m}^2/\text{yr}$$



In this example, the average geothermal heat flow is about 65 milliwatts per square meter.

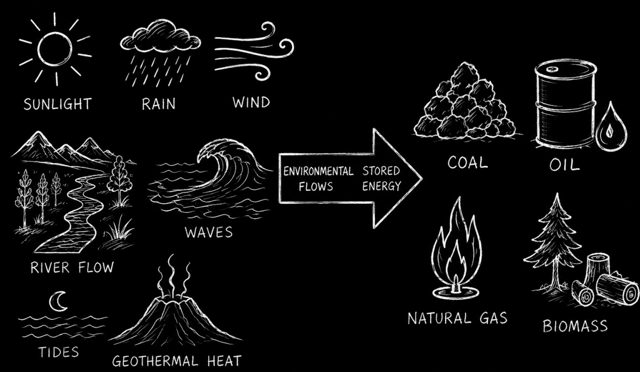
Applying the Carnot efficiency of 9.43 percent yields approximately 1.9×10^5 joules of available energy per square meter per year.

Compared with sunlight, geothermal energy is relatively small at Earth's surface, but it is continuously supplied and represents one of the fundamental energy sources supporting the geobiosphere.

Available Energy of Non-Renewable Sources…

For renewable resources we calculate available energy from physical processes.

For fuels, the available energy is measured directly from their heat of combustion.



Up to this point we have examined renewable resources that are continuously generated by environmental processes operating today. Nonrenewable fuels are different.

They represent renewable energy flows from the past that have been concentrated and stored over long periods of geological time.

Available Energy of Non-Renewable Sources…

Fossil Fuels

Fuel	Specific Energy (J/g)
Coal	32 kJ/g
Oil	45 kJ/g
Natural Gas	55 kJ/g
^{235}U	8×10^{10} kJ/g

Up to this point we have calculated available energy for renewable resources using thermodynamic relationships that describe environmental processes.

For fuels, the situation is much simpler. The available energy is measured directly as the heat released during complete combustion.

The values shown in this table are often called the specific energy, or heating value, of the fuel. They indicate how much energy is released when a unit mass of fuel is burned.

Notice that the values for fossil fuels are relatively similar. Coal, petroleum, and natural gas all contain on the order of tens of megajoules per kilogram. This reflects their common origin as concentrated organic matter produced by photosynthesis and subsequently transformed over geological time.

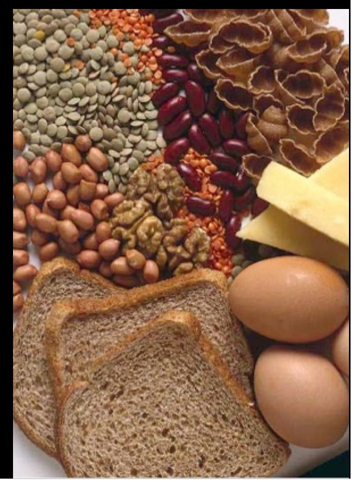
This distinction is one of the central ideas behind emergy analysis. Available energy tells us how much useful energy a fuel contains today, while emergy tells us how much environmental support was required to produce it.

The specific energy values in this table provide the starting point. In later lectures, we will multiply these energy quantities by Unit Emergy Values to estimate the total environmental contribution embodied in each fuel.

Available Energy of Non-Renewable Sources…

Organic Substances

Material	Specific Energy (J/g)
Organic Matter	14.6 – 37.7 kJ /g
Carbohydrates	16.7 kJ g-1
Proteins	20.9 kJ g-1
Fats	29.3 – 37.7 kJ g-1
Wood	14.6 – 22.6 kJ g-1



This table lists the specific energy of a variety of organic substances, including plant materials, animal tissues, and biological products.

The values represent the available energy released when these materials are oxidized. In other words, they estimate the amount of useful work that could potentially be driven by the organic matter.

Notice that most organic substances have similar energy contents, typically between about 15 and 25 megajoules per kilogram. This reflects their common origin in photosynthesis, where solar energy is captured and stored in chemical bonds.

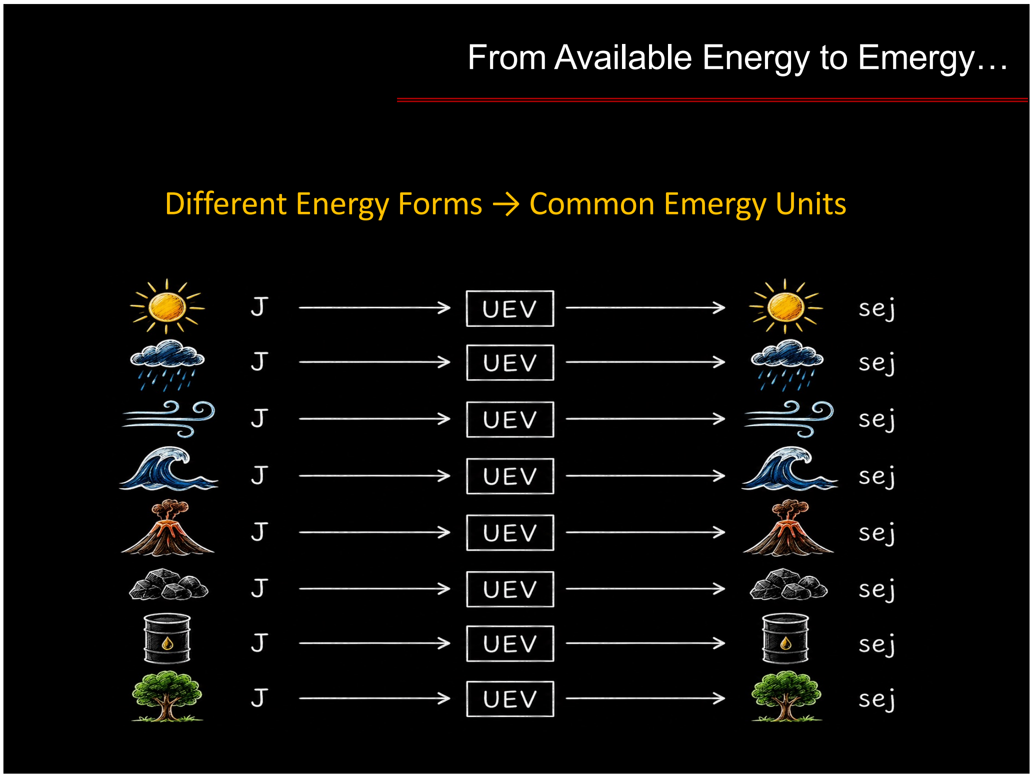
Some materials, such as fats and oils, contain more available energy per unit mass because their chemical structure stores more reduced carbon and hydrogen.

At first glance, it might appear that the energy content alone tells us how much useful work a substance can support. However, emergy theory suggests a deeper interpretation.

The ability of a resource to drive useful work depends not only on the energy it contains, but also on the amount of available energy previously required to produce it. Resources that require larger amounts of environmental work to create generally have a greater capacity to support useful work within human and natural systems.

For this reason, emergy uses the available energy previously required for production as a measure of a resource's potential contribution. By accounting for the environmental work required to create a product, emergy provides an estimate of its capacity to drive future work.

Thus, the specific energy values shown here tell us how much energy is contained in these materials, while emergy helps us understand their potential significance within larger systems of energy transformation.



In this lecture we calculated energy in several different ways. For sunlight, we calculated absorbed radiant energy.

For wind, waves, tides, and rivers, we calculated mechanical energy or energy dissipated by motion.

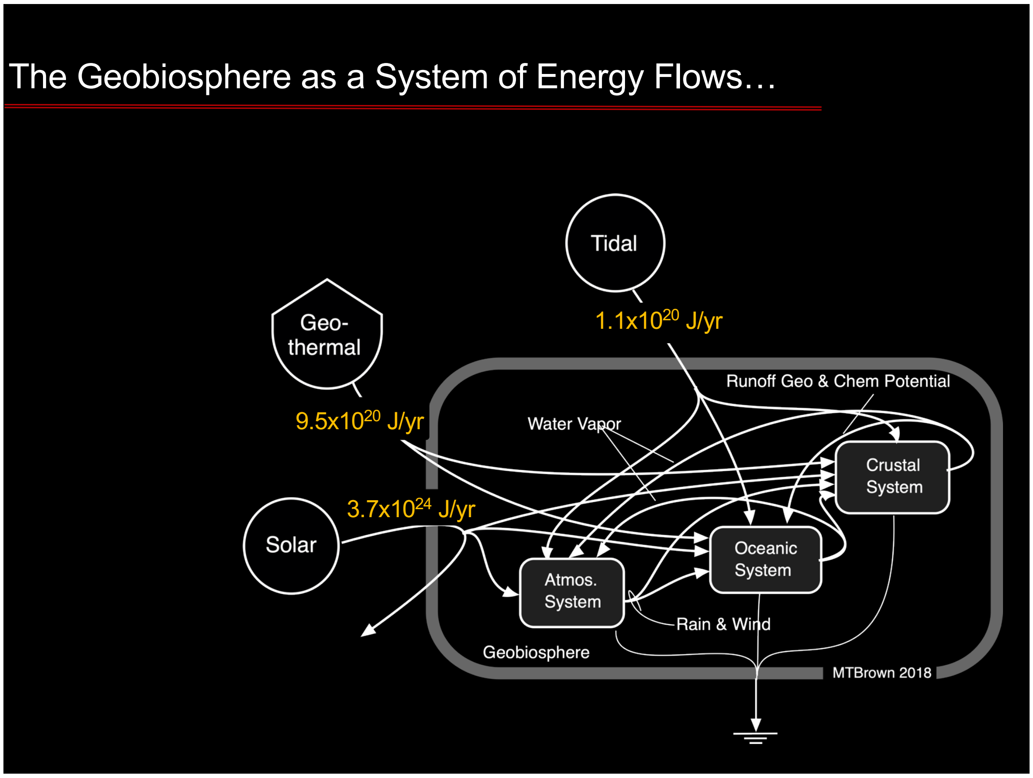
For rainfall and river water, we calculated chemical potential energy. For geothermal heat, we estimated the available fraction of a thermal gradient.

For fuels and organic substances, we used heat of combustion.

These calculations do not all measure the same process. Each calculation estimates the energy expressed through the physical or chemical process appropriate to that resource.

The next step is emergy. Emergy asks how much available energy was previously required to produce a resource. That prior environmental work provides a way to estimate the resource's ability to support future useful work in larger systems.

In the next lecture, we will take the energy values calculated here and multiply them by Unit Emergy Values to calculate emergy.



The Earth is an open thermodynamic system driven by three independent sources of available energy.

Solar radiation is the largest of these inputs and drives atmospheric circulation, evaporation, precipitation, and biological production throughout the geobiosphere.

Tidal energy originates from gravitational interactions among the Earth, Moon, and Sun, while geothermal energy originates within the Earth's interior.

Through interactions among the atmosphere, oceans, and crustal systems, these three primary energy sources generate the secondary flows we have examined in this lecture, including wind, rainfall, river flow, waves, and ocean currents.

The values shown on this diagram represent the annual available energy supplied by the three primary driving sources.

We can now combine these results with the calculations for the secondary flows and compare their relative contributions to the operation of the geobiosphere.

Available Energy of the Geobiosphere

Energy Flow	Production (J/yr)
Global solar radiation	3.7×10^{24}
Global tide	1.1×10^{20}
Global geothermal	9.5×10^{20}
Global wind circulation	2.3×10^{22}
Global Rain chemical pot.	5.3×10^{20}
Global river geopotential	2.9×10^{20}
Global river chemical pot.	1.8×10^{20}
Global waves at the shore	7.6×10^{19}
Global ocean current	9.5×10^{19}

The table summarizes the annual available energy contained in the major flows supporting the geobiosphere.

The three primary driving sources—solar, tidal, and geothermal energy—appear at the top of the table, followed by the secondary flows generated through their interaction within the Earth system.

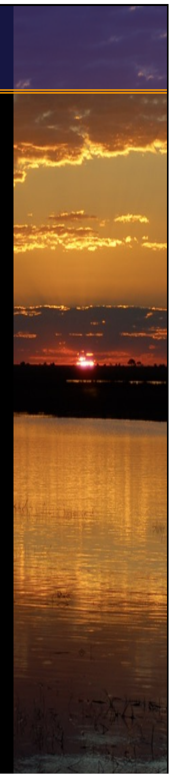
Several patterns are immediately apparent. Solar radiation is by far the largest energy input to the geobiosphere, exceeding all other flows by several orders of magnitude.

Wind circulation represents the largest of the secondary flows, while rainfall, river flow, tides, waves, ocean currents, and geothermal heat contribute smaller but still important quantities of available energy.

Together these flows provide a quantitative description of the energetic basis of the geobiosphere.

Having estimated the available energy contained in these environmental flows, we are now prepared to ask a different question: How much environmental support is required to generate them?

Thank You...



Thank You for Your Attention

感谢您的聆听