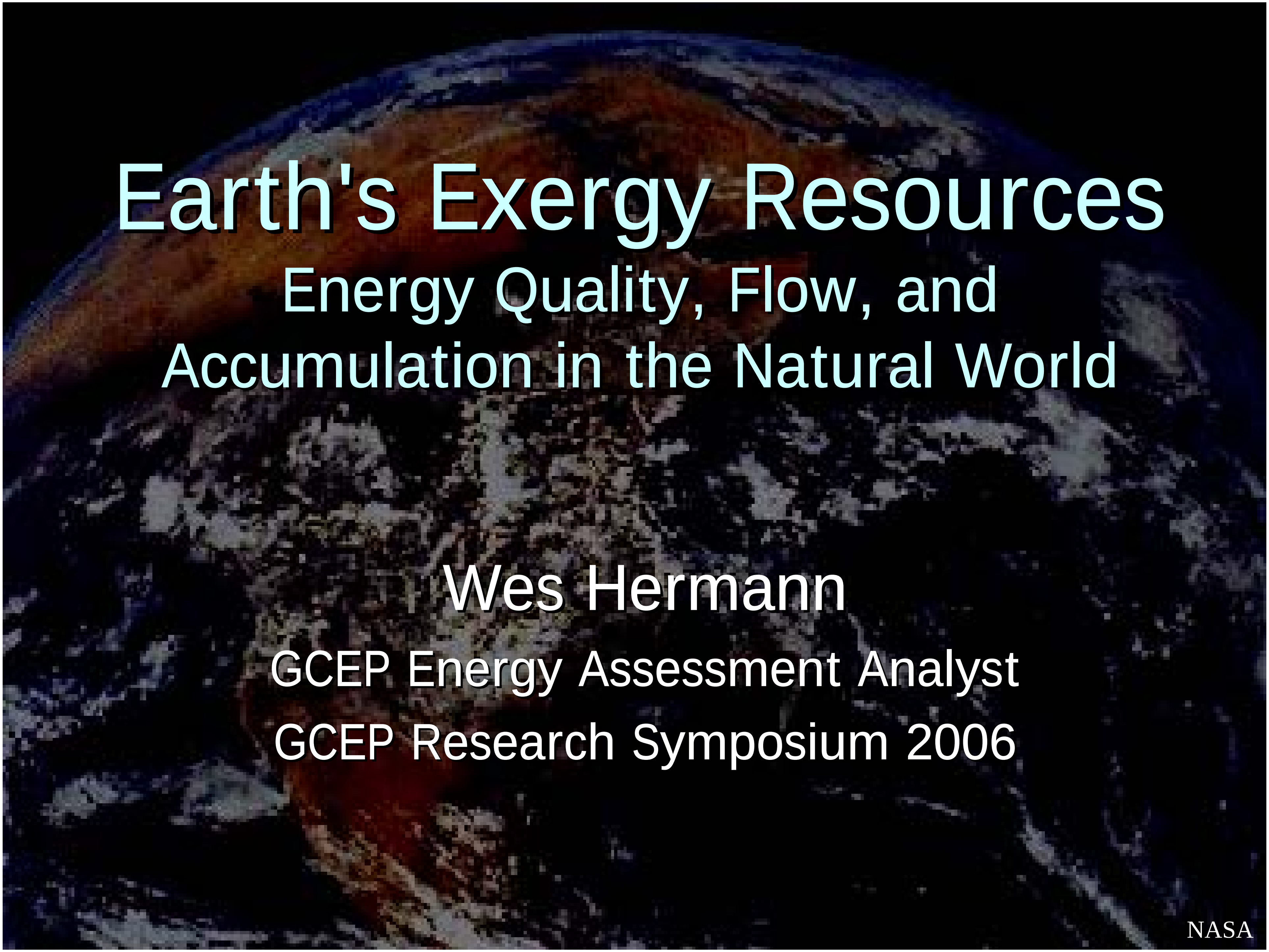

Earth's Exergy Resources

Energy Quality, Flow, and Accumulation in the Natural World

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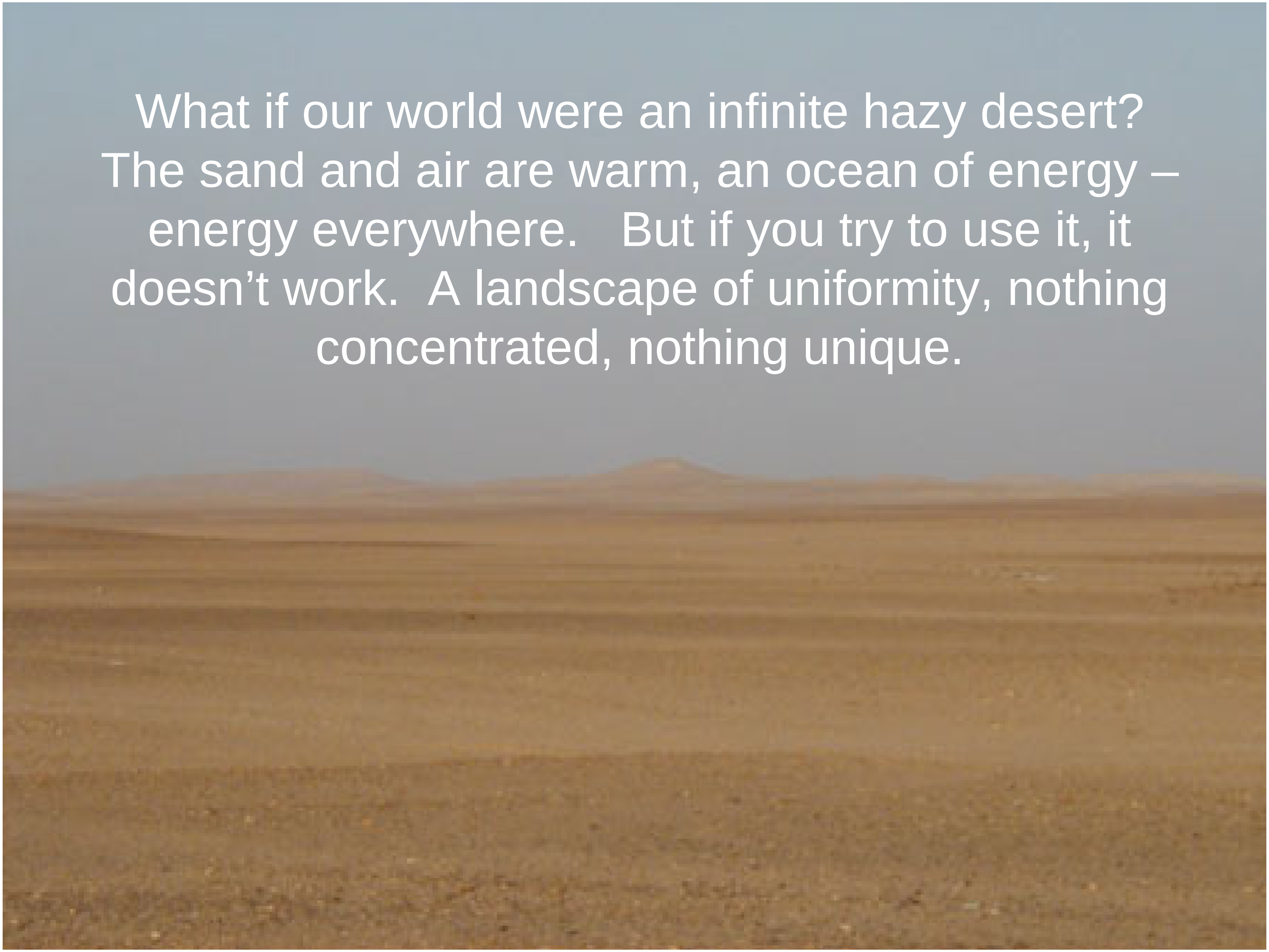
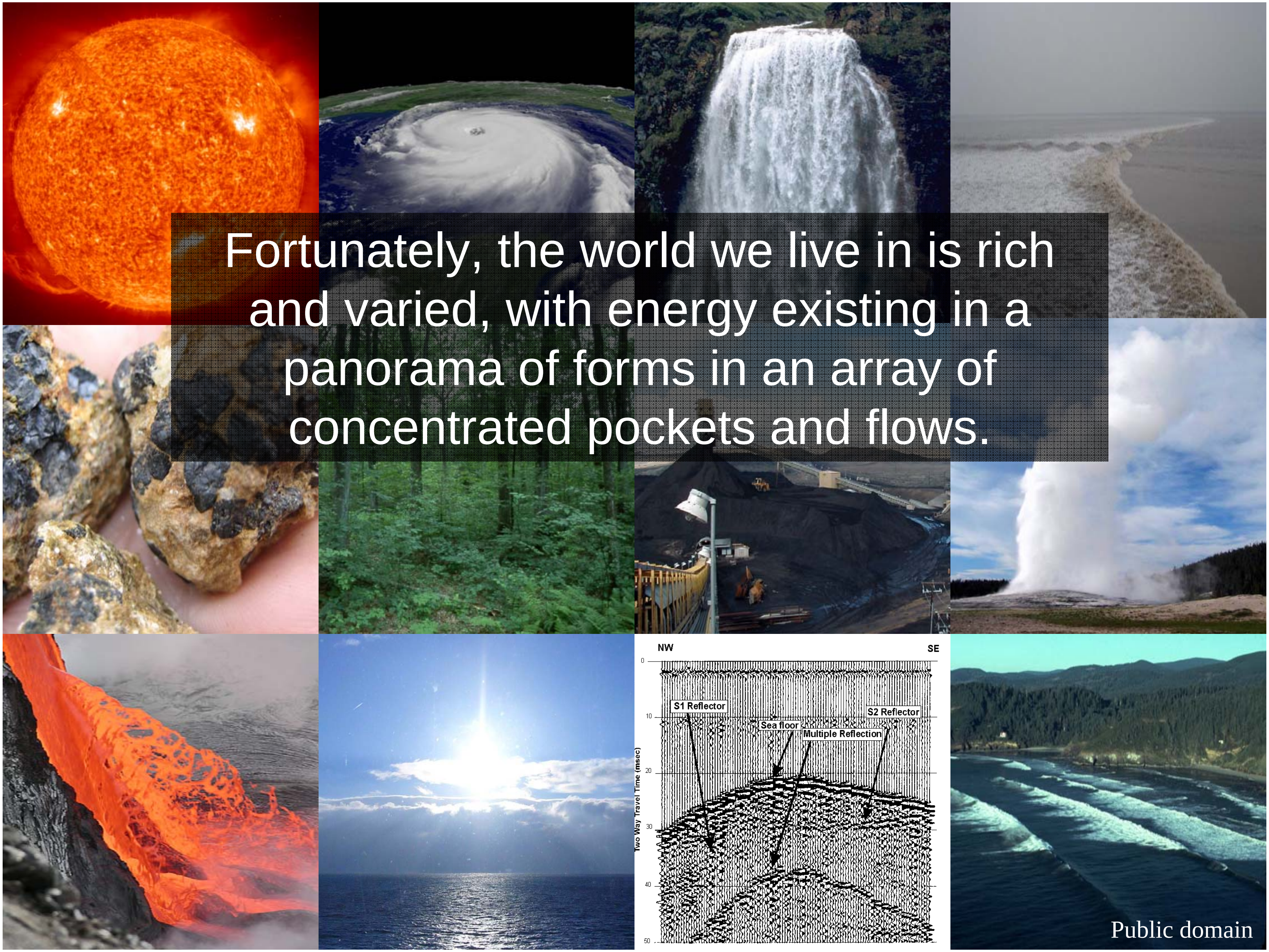
GCEP Research Symposium 2006

NASA


What if our world were an infinite hazy desert?
The sand and air are warm, an ocean of energy –
energy everywhere. But if you try to use it, it
doesn't work. A landscape of uniformity, nothing
concentrated, nothing unique.

Fortunately, the world we live in is rich and varied, with energy existing in a panorama of forms in an array of concentrated pockets and flows.



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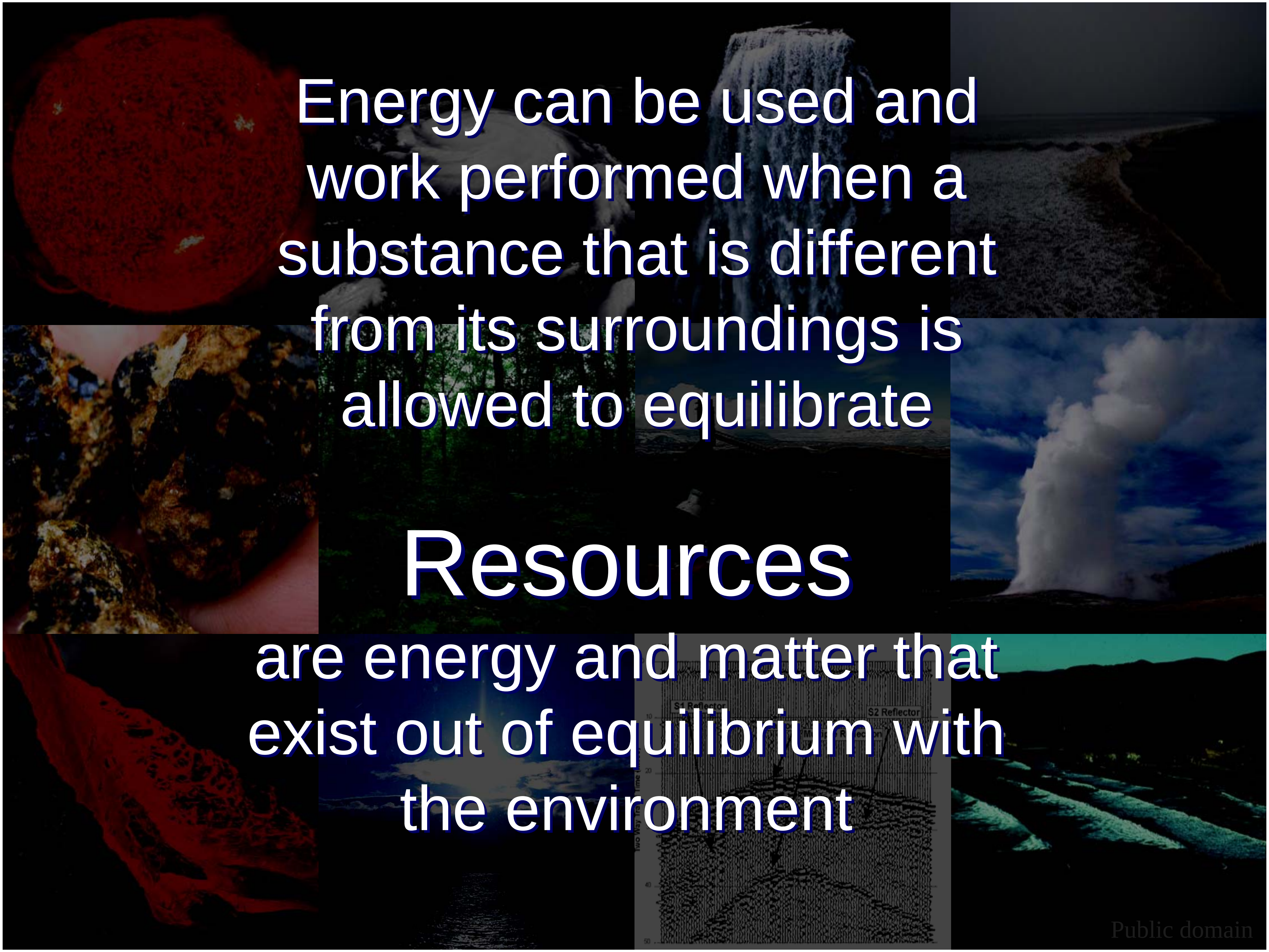

Energy can be used and work performed when a substance that is different from its surroundings is allowed to equilibrate
Resources
are energy and matter that exist out of equilibrium with the environment
Public domain

The environment

- The character and composition of the environment determines the work potential of a resource.
- A reference state for temperature, motion, compounds and elements.

- Atmosphere

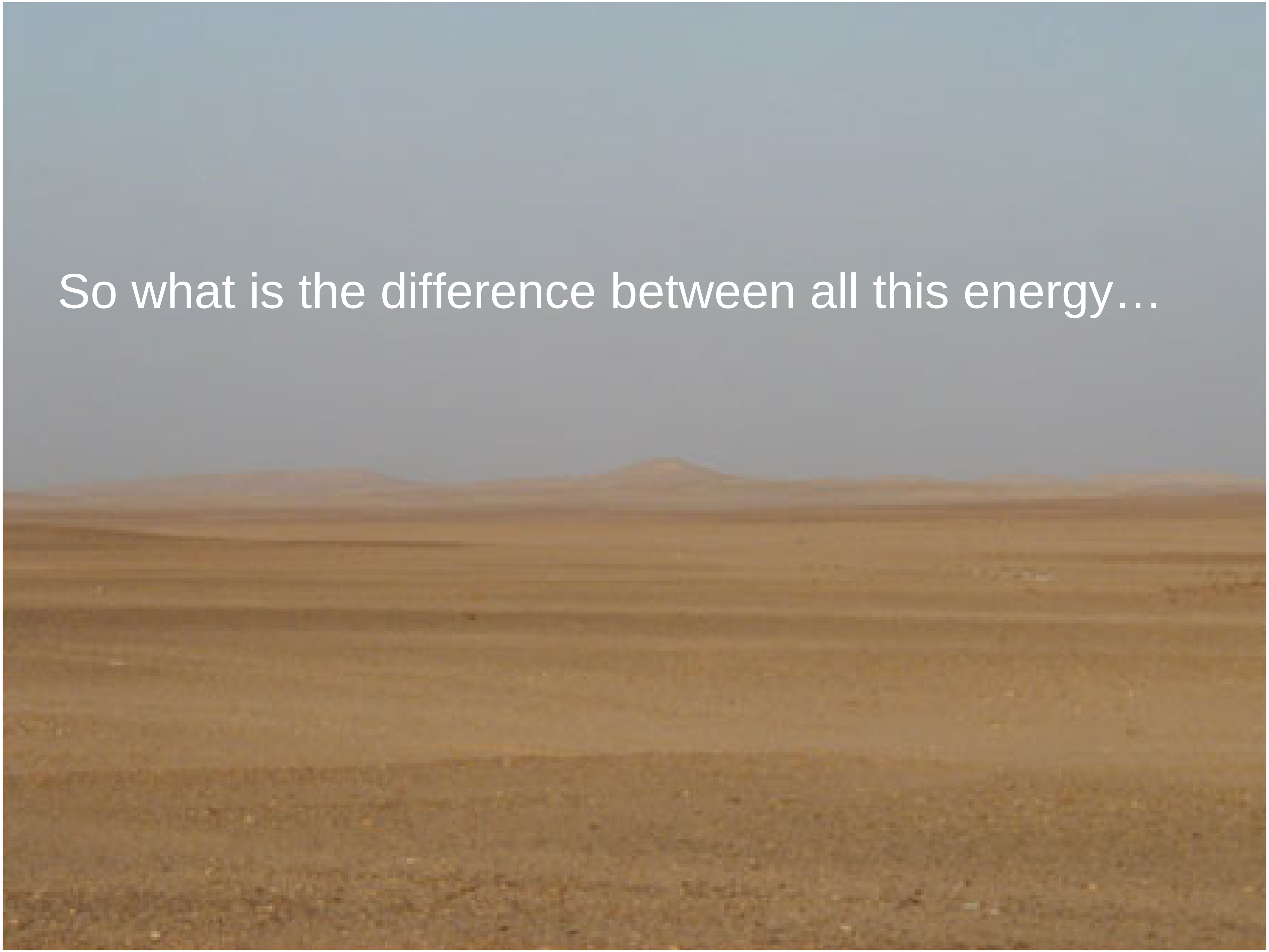
N_2, O_2, H_2O, Ar, CO_2, Ne, He...

- Ocean

H_2O, Cl^-, Na^+, SO_4^{2-}, Mg^{2+}...

- Crust

SiO_2, Fe_3O_4, Al_2O_3, Cu_2S...



So what is the difference between all this energy…

…and these forms of energy? Isn't there some common currency with which we can compare the usefulness of different forms of energy and speak only about the part we want?

Public domain

exergy

is a measure of work potential or disequilibrium from the environment

While

exergy can be destroyed, energy cannot

exergy is the useful portion of energy

exergy

is what most mean when they say energy

How does exergy relate to energy?

Energy quality

- Exergy is defined by combining the 1st and 2nd laws of thermodynamics: "energy is conserved" and "things fall apart".
- Energy quality is the ratio of exergy to energy.

  Q = X/E   or   Exergy = Q * Energy
- Energy that is 30% useful has a quality of 0.3.

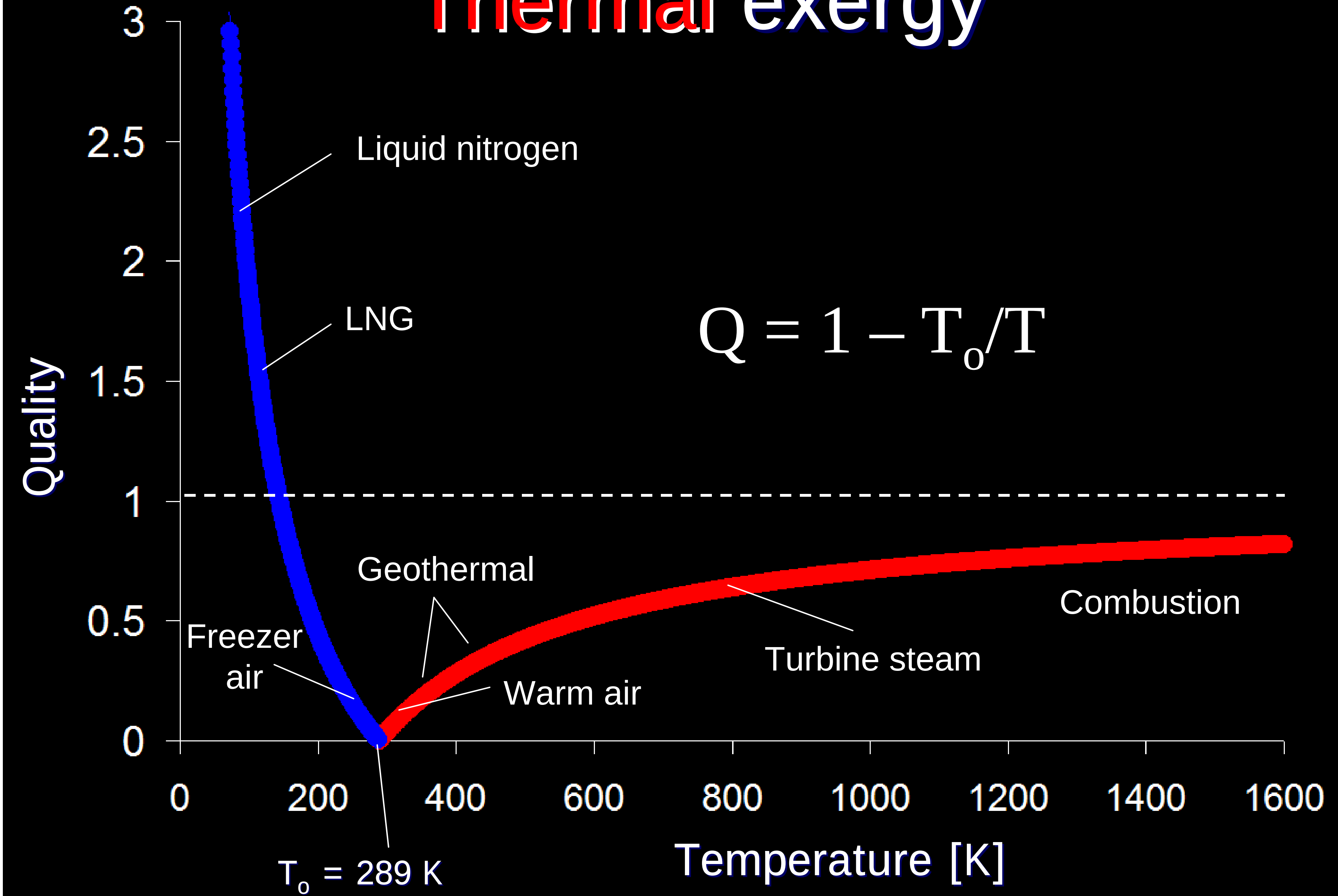
  100 J of energy in this form contains 30 J of exergy.
- Multiply the energy by the quality to obtain exergy. 100 J * 0.3 = 30 J.
- In some cases, the quality can be greater than 1.
- Exergy comes in the same forms as energy:

  Kinetic, gravitational, thermal, radiation, chemical, nuclear

Kinetic and gravitational exergy

- Motion relative to the environment or height relative to the “ground”.
- Kinetic and gravitational exergy always have Q = 1, or the exergy and energy are equal.
- No temperatures, compounds, or internal degrees of freedom.
- That was easy!

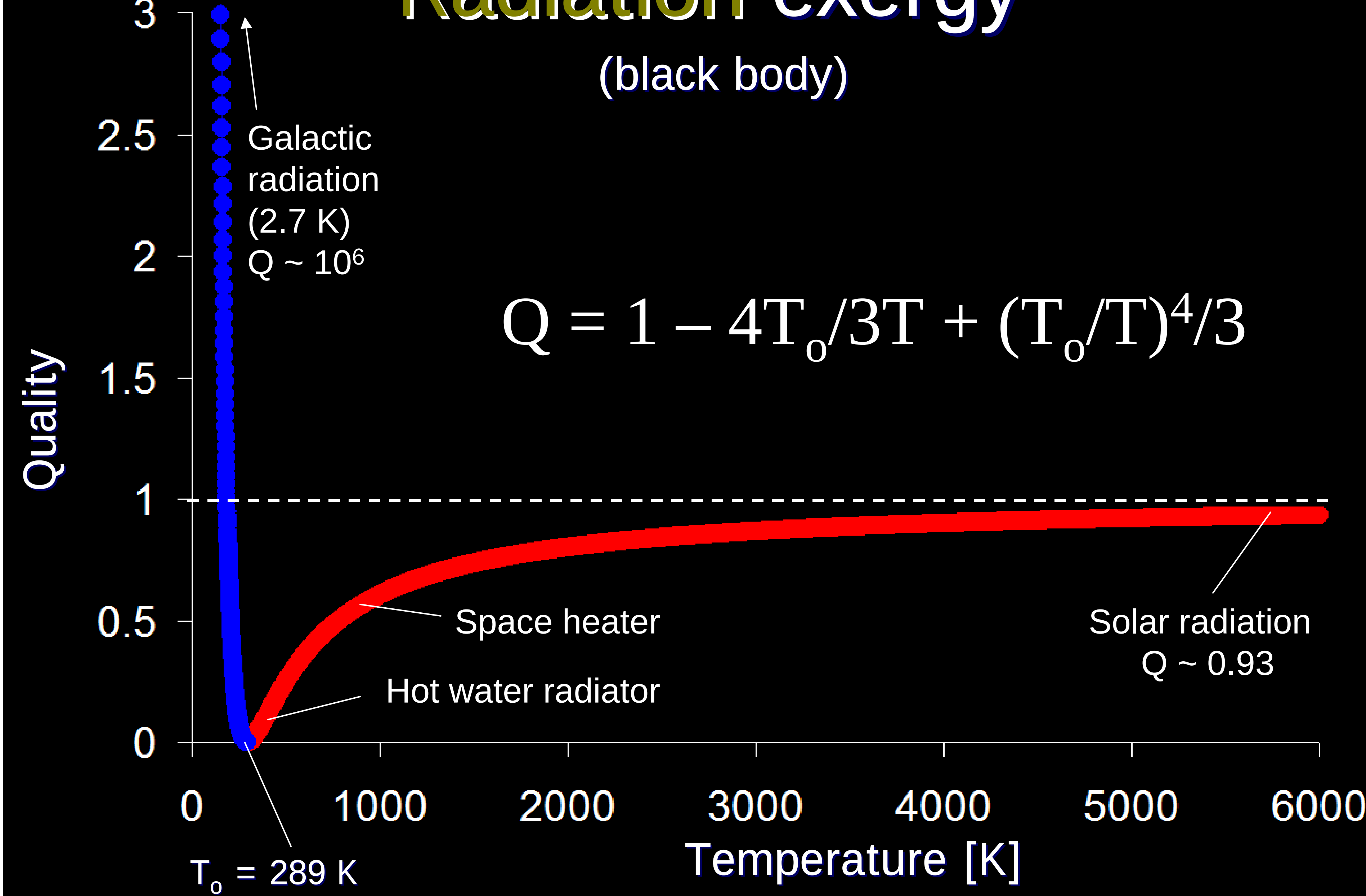
Thermal exergy



Radiation exergy

(black body)

$$Q = 1 - 4T_o/3T + (T_o/T)^4/3$$



Chemical exergy

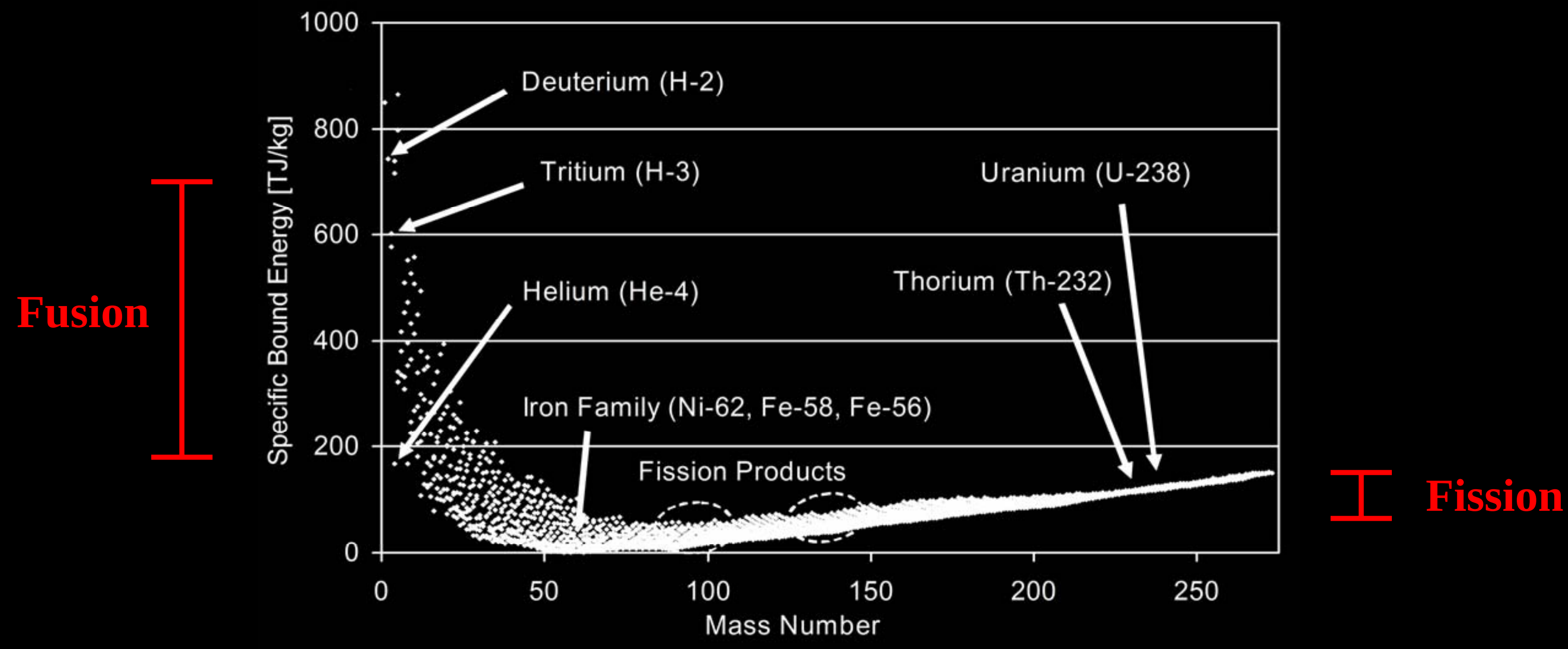
Chemical exergy = Bond potential + “degrees of freedom” potential + diffusive potential

These values depend on the chemicals commonly found in the environment, and can be looked up in tables

Chemical name	Bond potential	“DOF” potential	Diffusive potential	Chemical exergy	Q
	[MJ/kg]				
Methane	50.0	-0.1	2.0	51.9	1.037
Octane	44.7	1.3	1.5	47.5	1.063
Ethanol	27.7	0.8	1.1	29.6	1.067
Acetylene	48.3	-1.2	1.6	48.7	1.008
Hydrogen	120.0	-8.4	5.6	117.2	0.977
Aluminum	31.0	-0.8	2.7	32.9	1.061
Freshwater	0	0	0.0049	0.0049	n/a

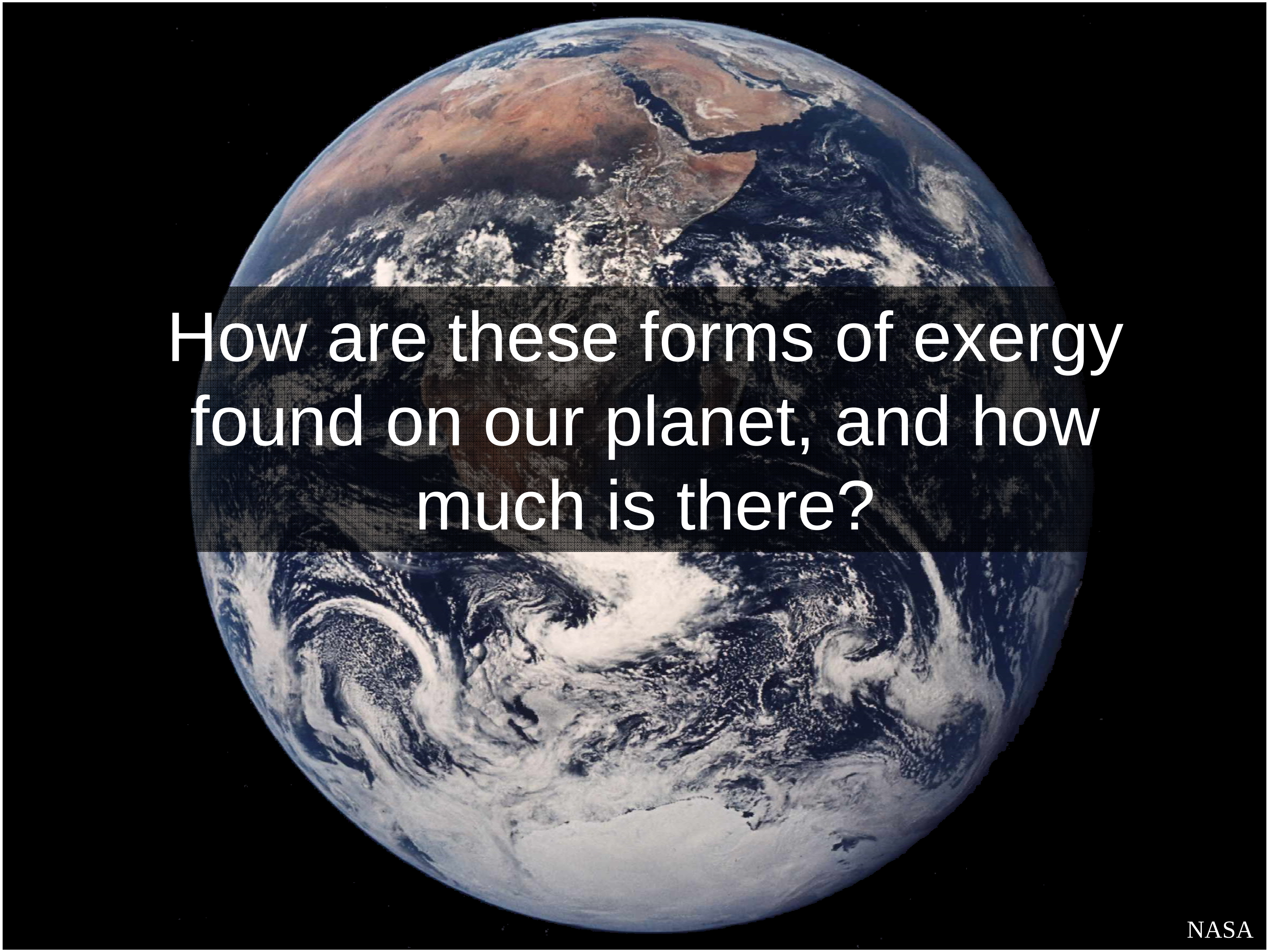
Nuclear exergy(?)

Nuclear exergy = Bond potential + "degrees of freedom" potential? + diffusive potential?
Problems: non-conservation of atoms, hadrons, quarks; nearly all matter is a fuel.

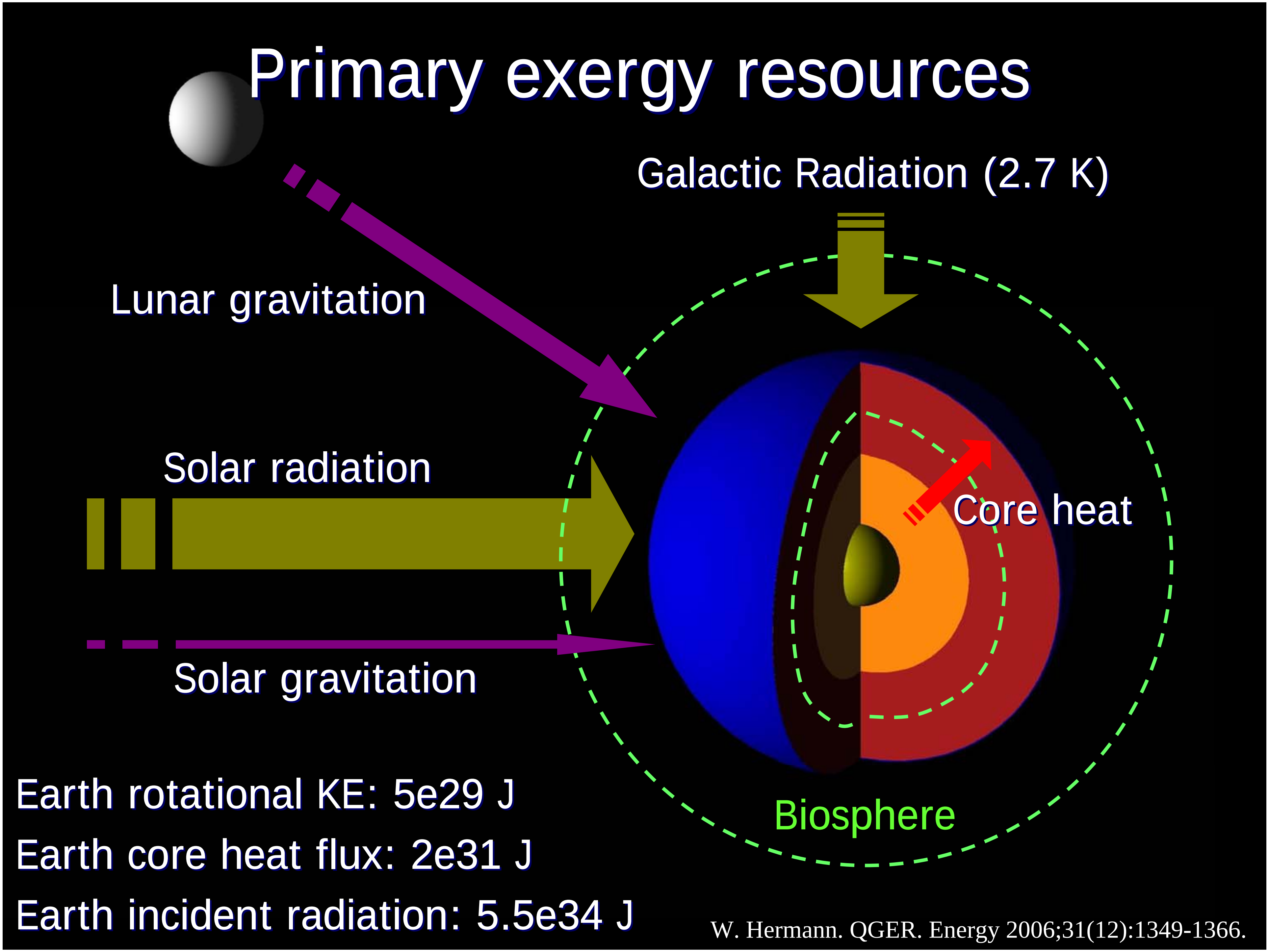


Assumptions:
Q = 0.95-1 (bond potential only, ignore neutrinos)
"Turn on" only U-235, U-238, Th-232, Li-6, Li-7, H-2

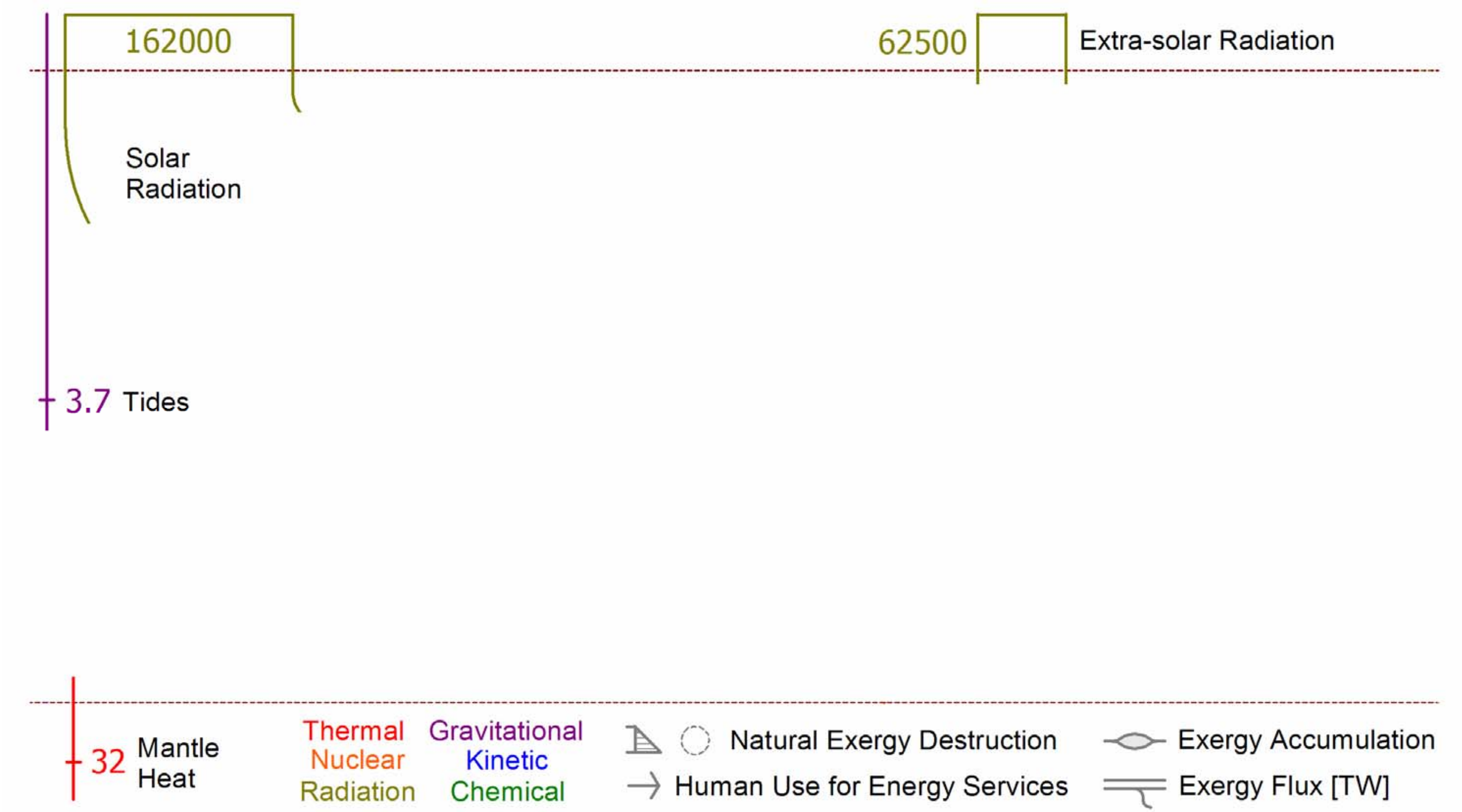
How are these forms of exergy found on our planet, and how much is there?



NASA


Primary exergy resources
Galactic Radiation (2.7 K)
Lunar gravitation
Solar radiation
Core heat
Solar gravitation
Biosphere
Earth rotational KE: 5e29 J
Earth core heat flux: 2e31 J
Earth incident radiation: 5.5e34 J
W. Hermann. QGER. Energy 2006;31(12):1349-1366.

Exergy flux, accumulation, destruction, and use



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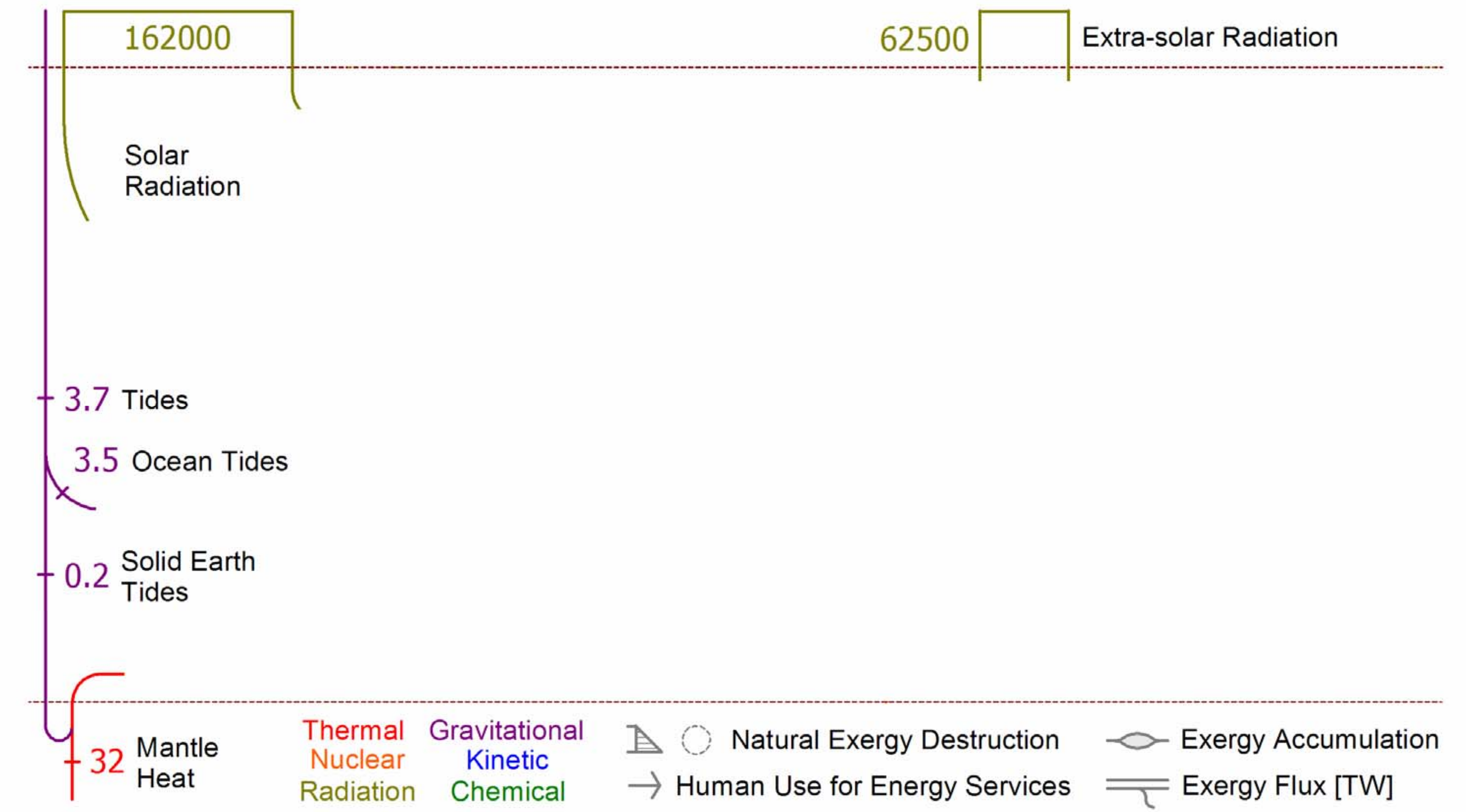
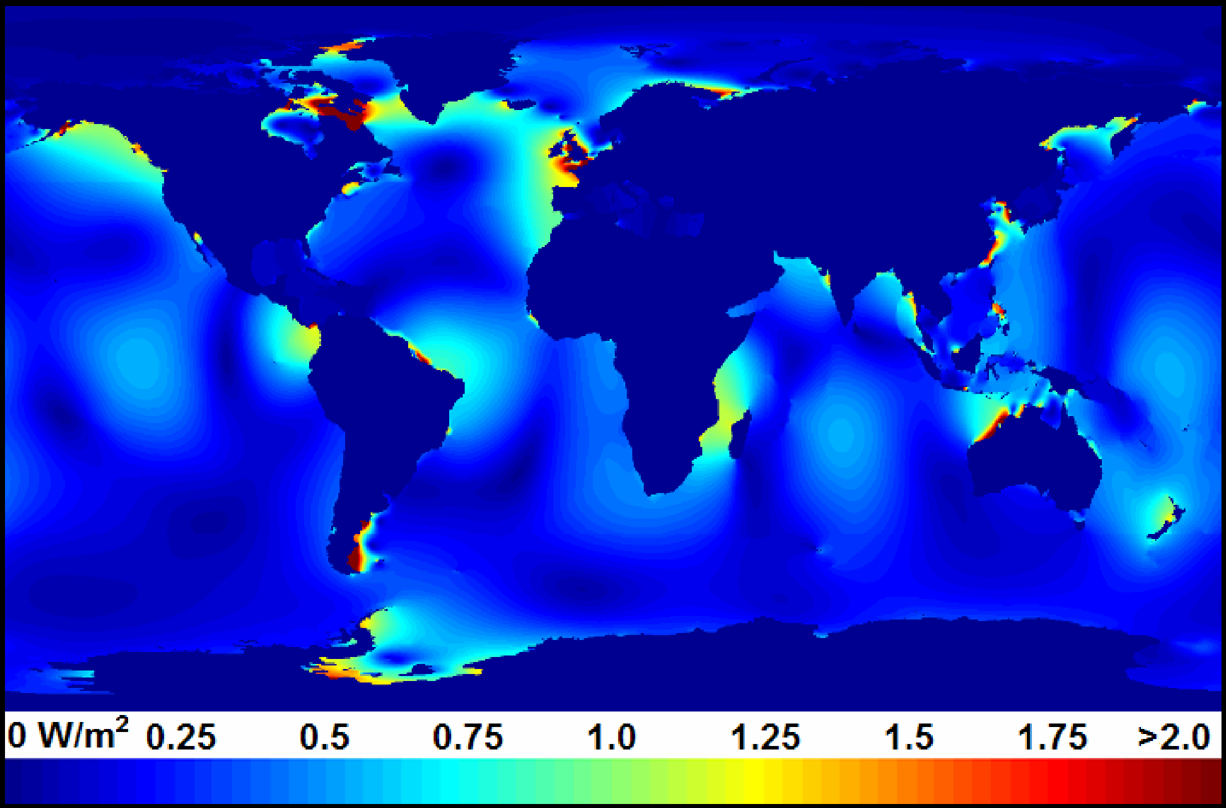


W. Hermann. Quantifying Global Exergy Resources. Energy 2006;31(12):1349-1366.

Ocean tides

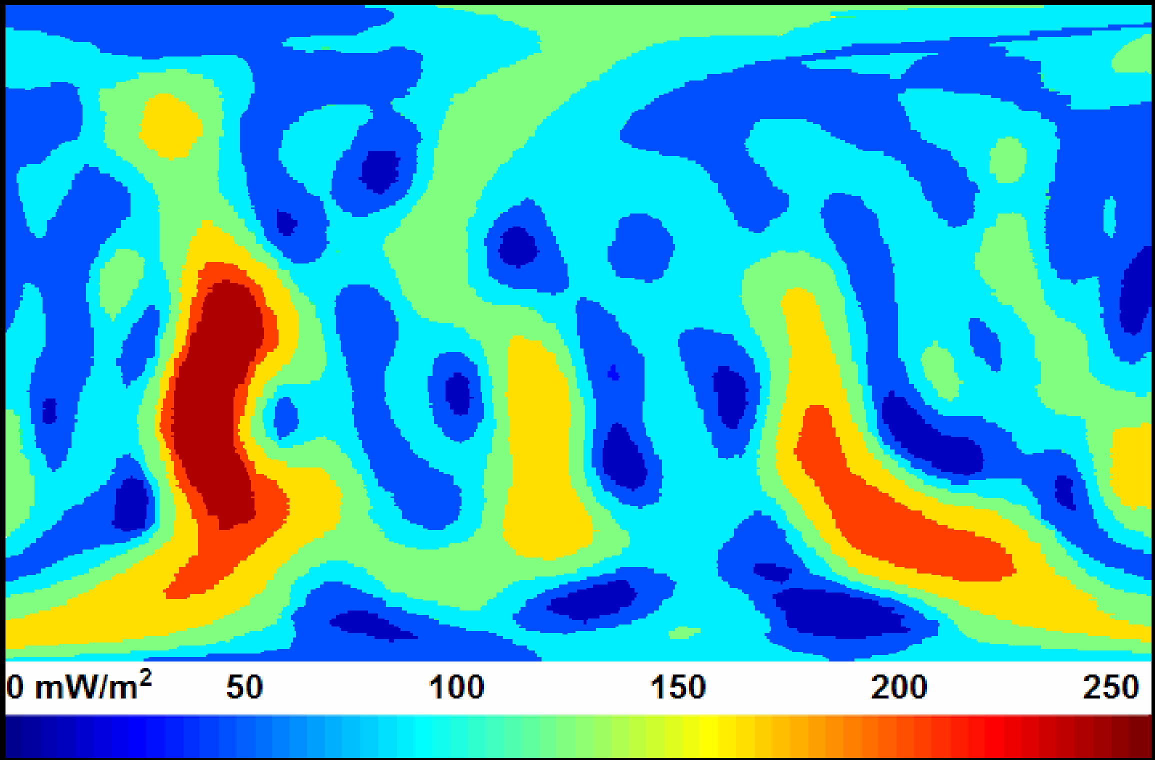
- Lunar tides represent 70% of dissipation.
- 2.5 TW dissipate on shallows and shelves, 1.0 TW dissipate in deep ocean.
- 10 kJ for each m^2 of ocean surface and m of tidal range.



Lefèvre, F., F. Lyard, C. Le Provost, and E.J.O. Schrama, FES99 Global Tide Model, 2001

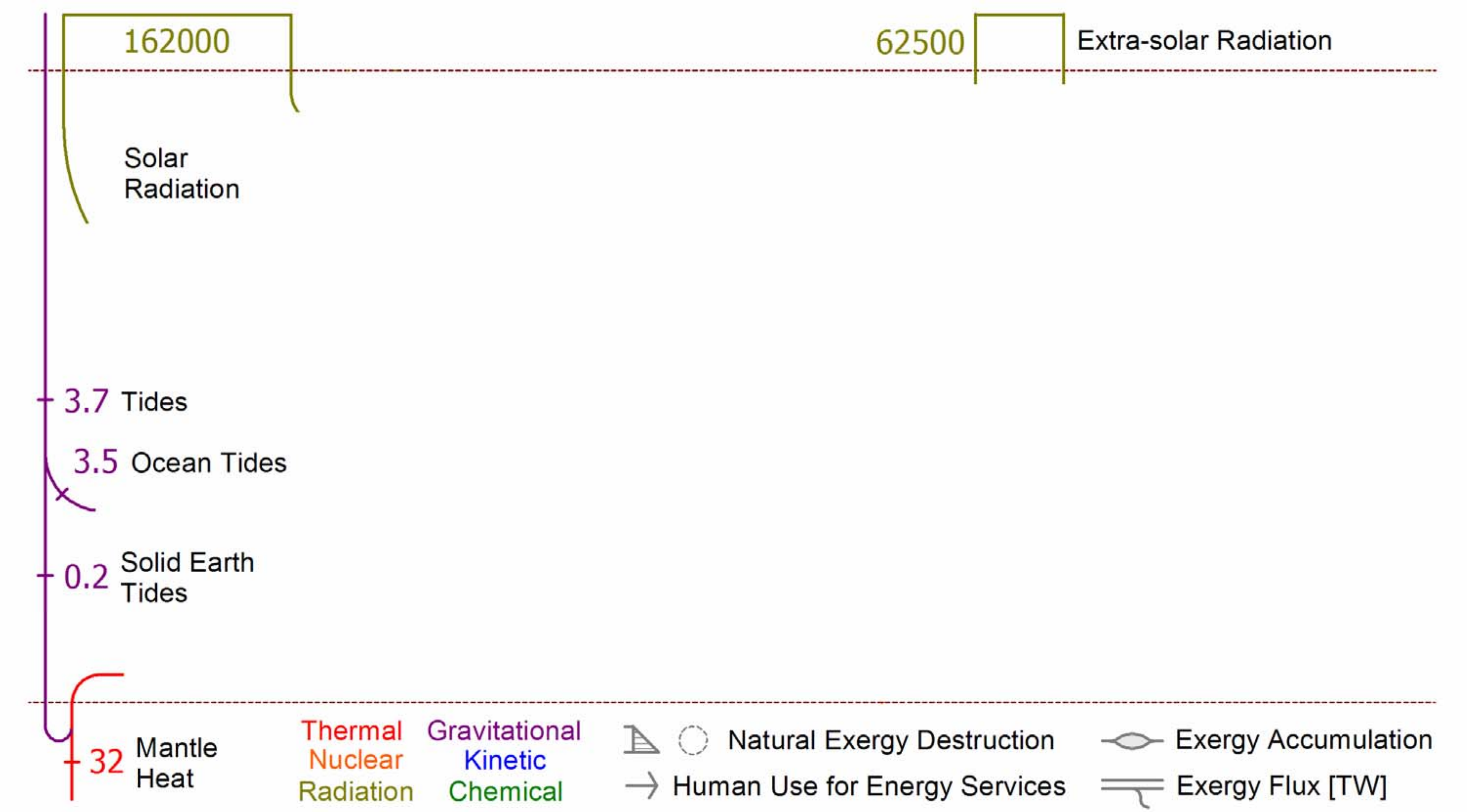
Geothermal heat

- Nuclear decay and spontaneous fission generate 30 TW thermal energy but energy conduction and convection is about 45 TW, cooling the core.
- With Q = ~0.7 at 40 km deep, exergy flow is 32 TW.



Pollack HN, Hurter SJ, Johnson JR. Heat flow from the Earth's interior: analysis of the global data set. Rev Geophys 1993;31(3):267–80.

Exergy flux, accumulation, destruction, and use



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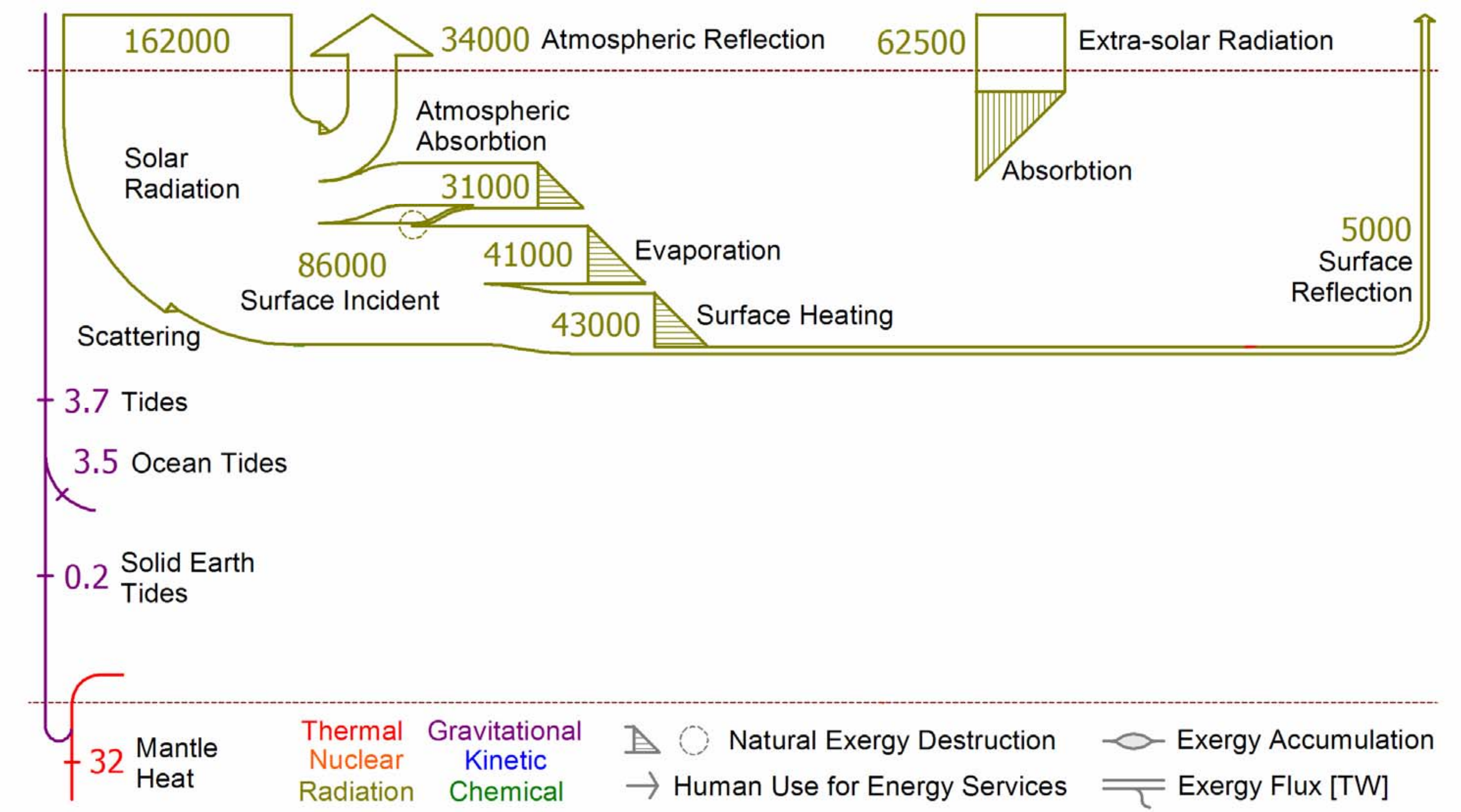

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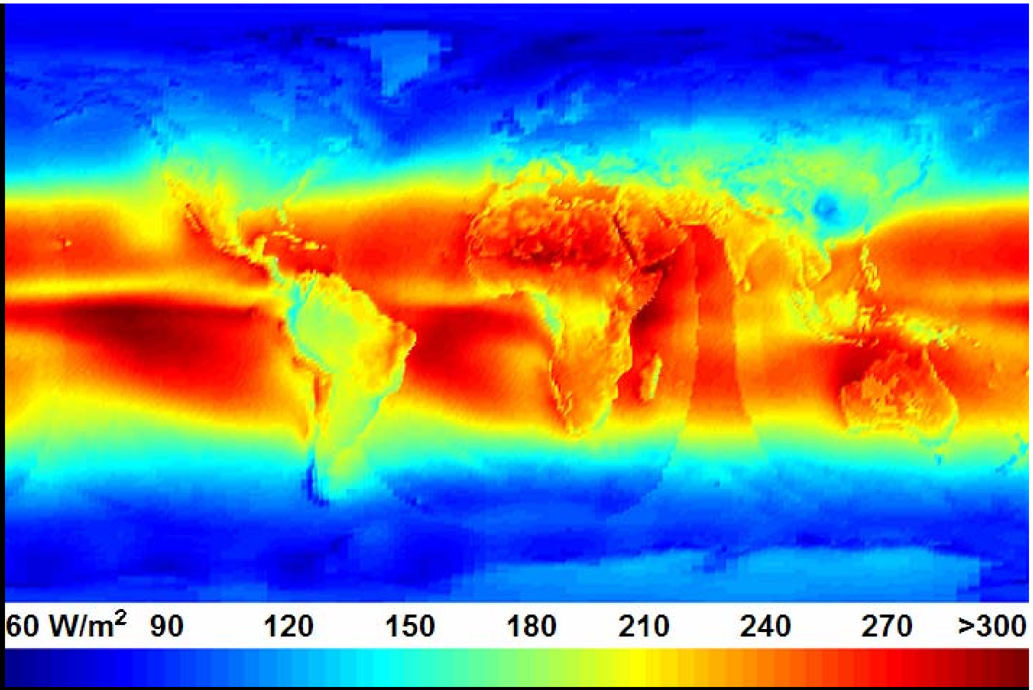
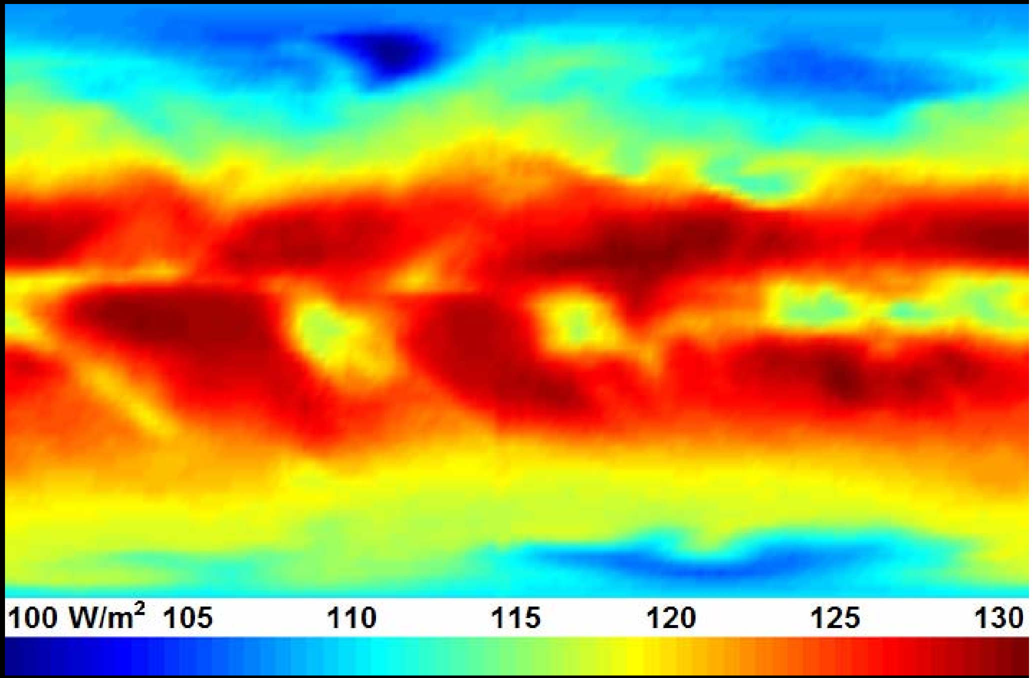
Radiation exchange

- Peak insolation is ~1000 W/m^2.
- Global average insolation is 168 W/m^2.
- Diffusion decreases radiation temperature.

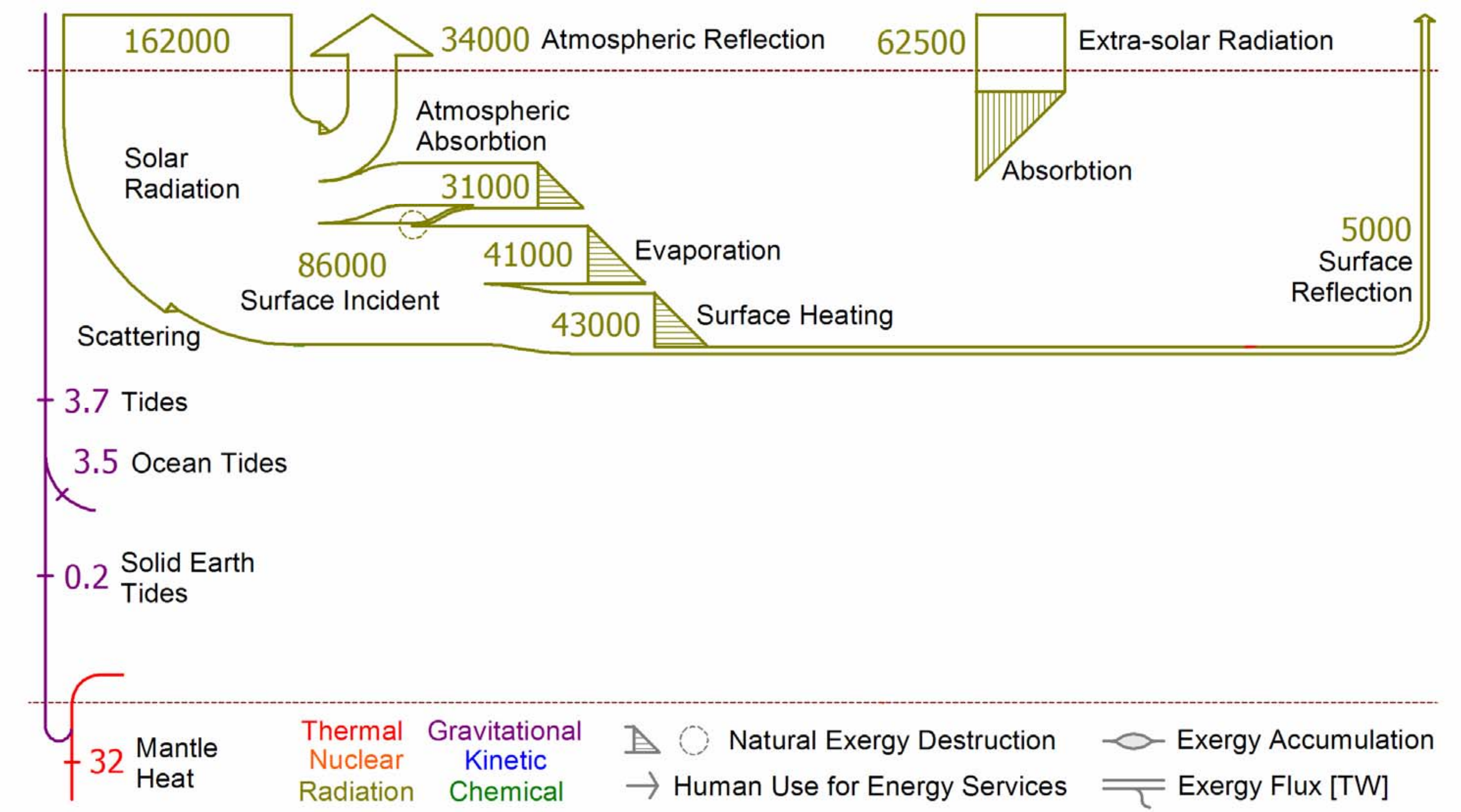
- Average extra-solar radiation exergy is 121 W/m^2.
- Extra-solar radiation is mostly absorbed in the atmosphere.





NASA CERES, GSFC; NASA. Surface meteorology and solar energy. Earth Science Enterprise Program. NASA LRC, 2004.

Exergy flux, accumulation, destruction, and use



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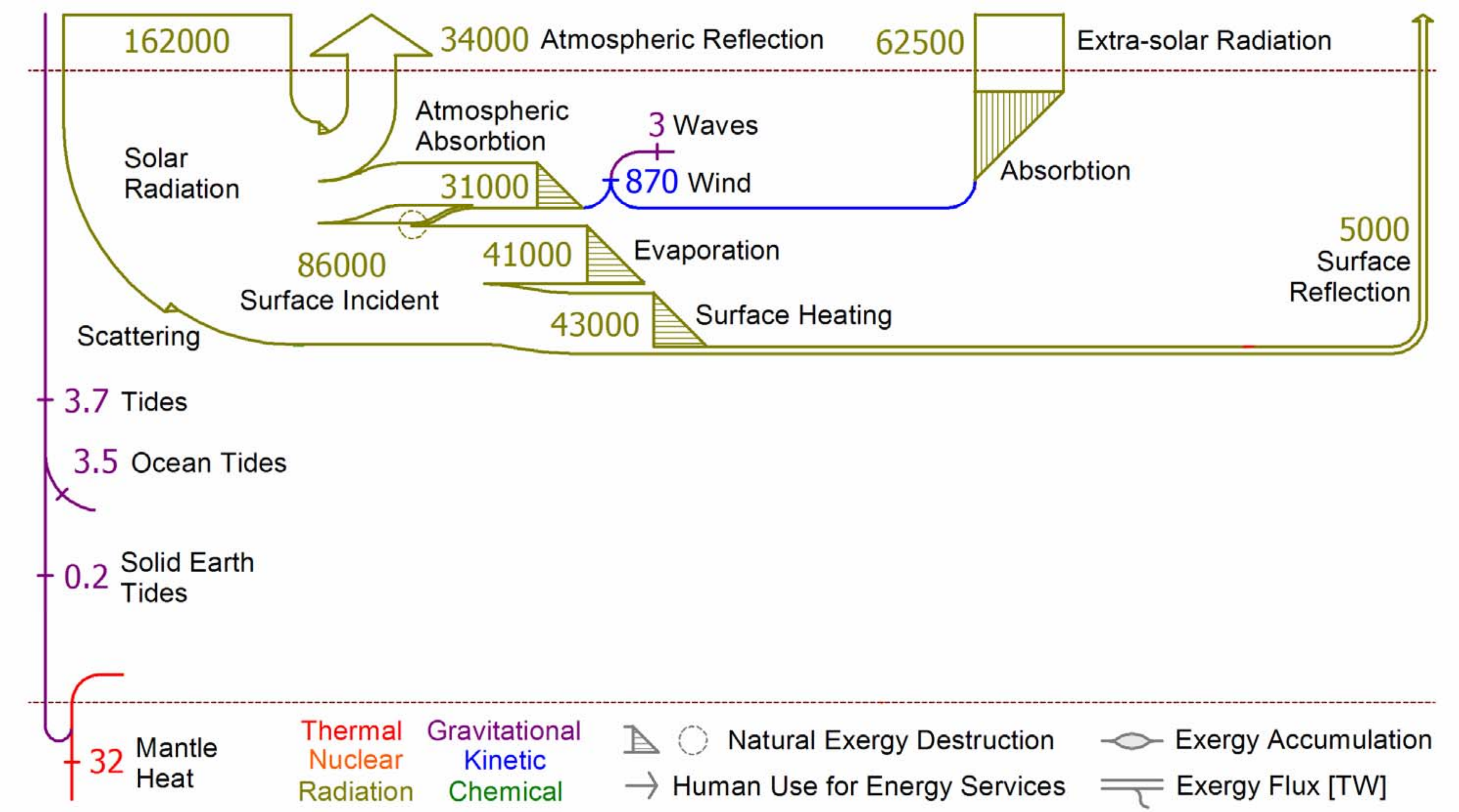

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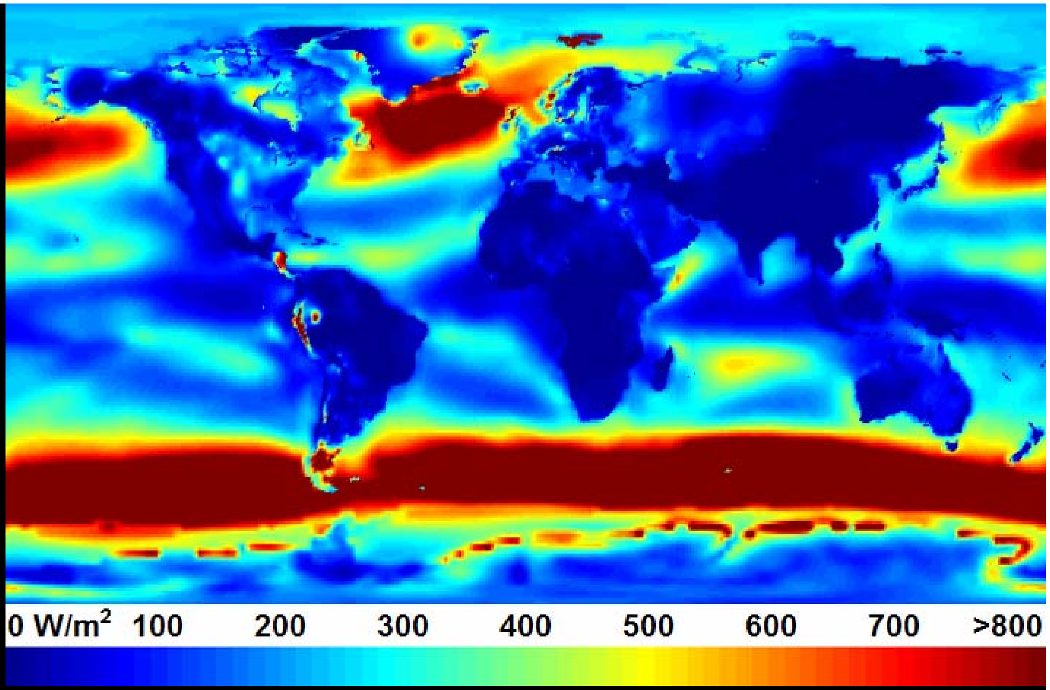
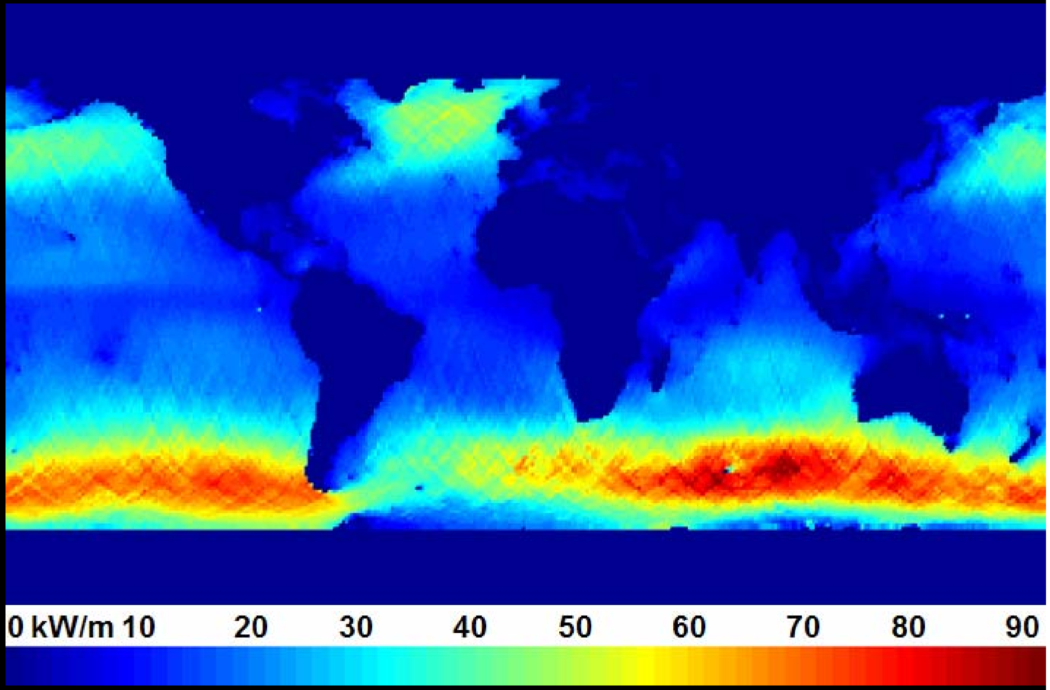
Wind and waves

- One third of wind exergy is within the surface boundary layer.
- Global average wind speed at 50m is 6.6 m/s, providing 330 W/m².

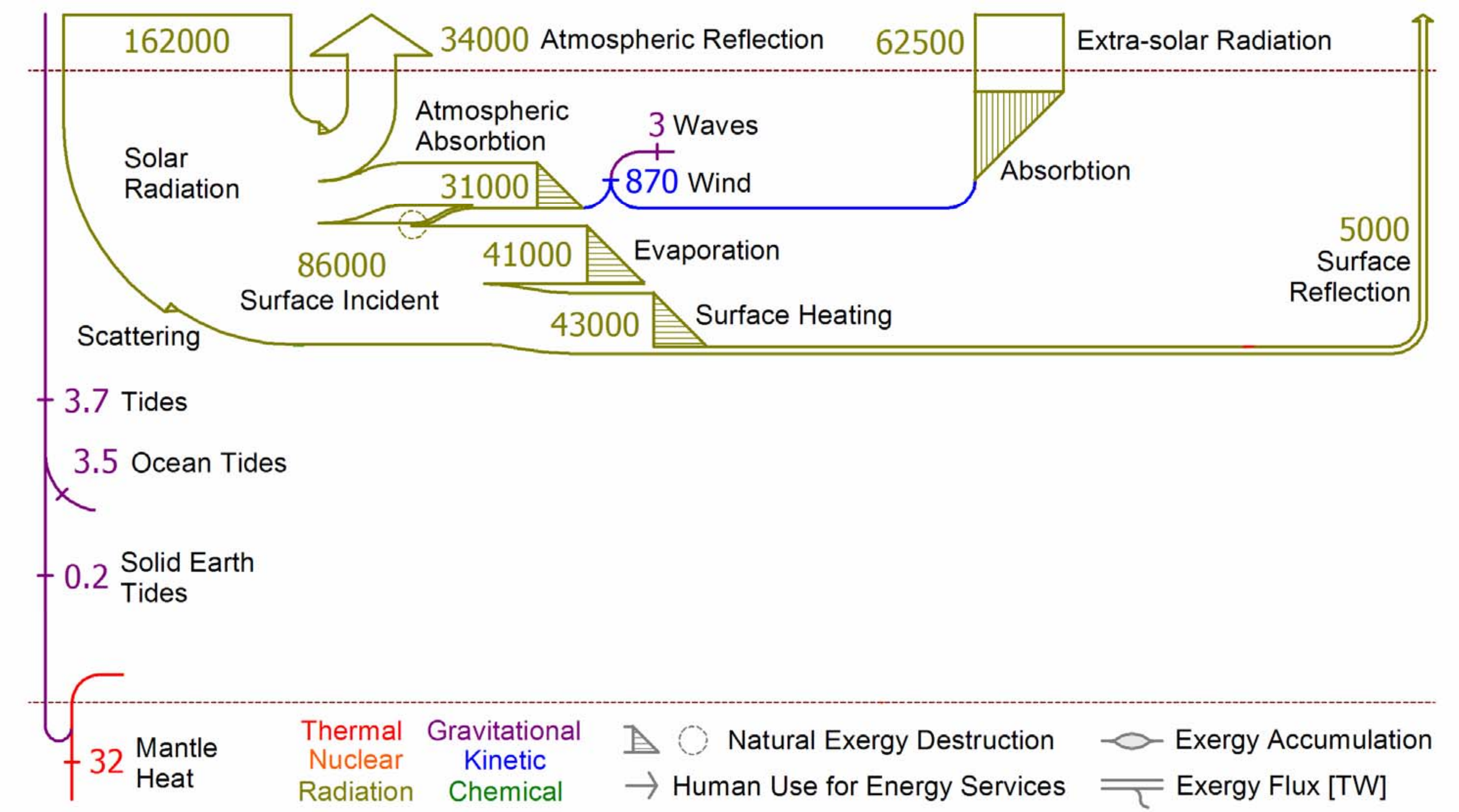
- 60 TW ocean waves dissipate to 3 TW shore waves.
- Open coast wave energy varies from 10-100 kW/m.





Jason-1, NASA/CNES; NASA. Surface meteorology and solar energy. Earth Science Enterprise Program. NASA LRC, 2004.

Exergy flux, accumulation, destruction, and use



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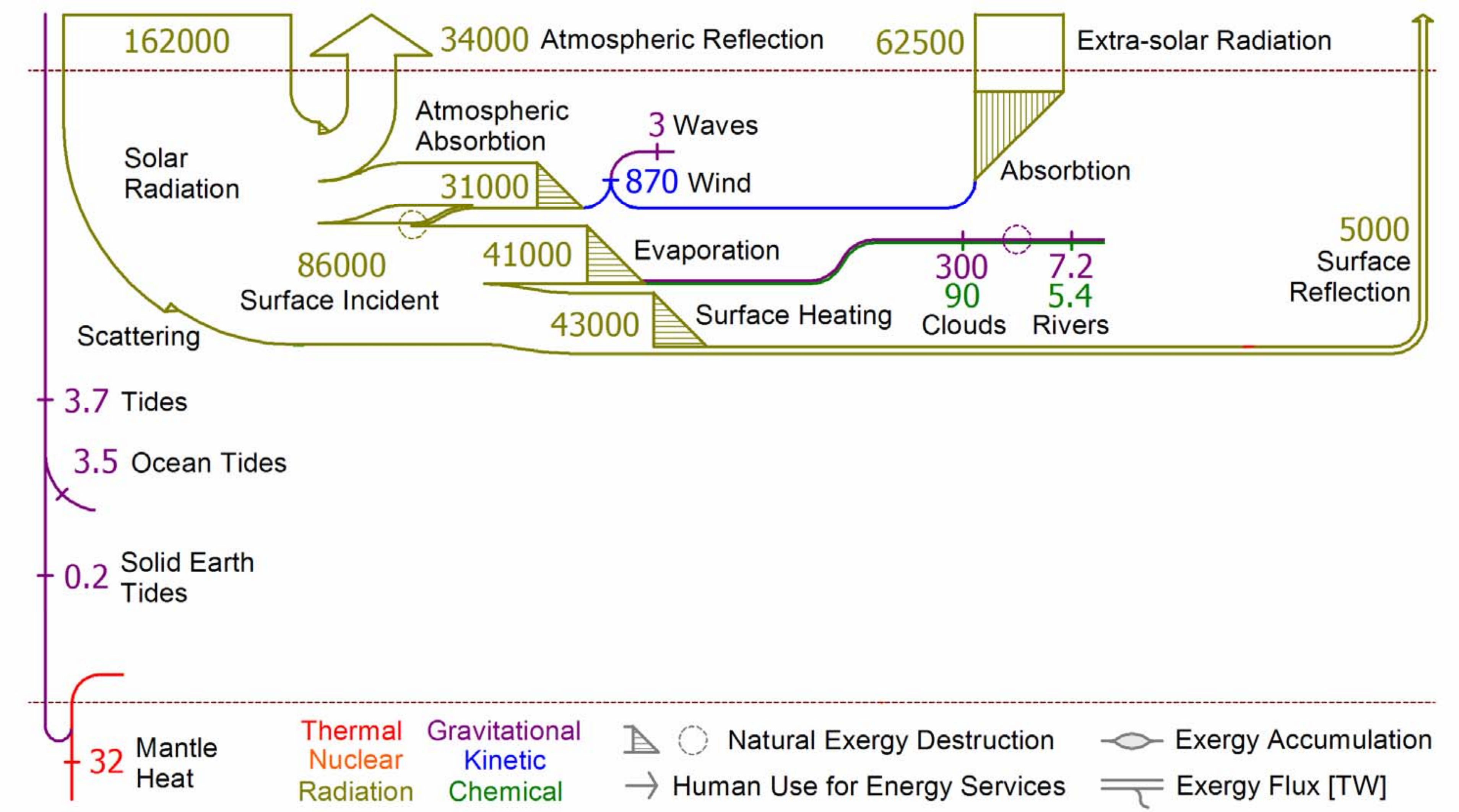
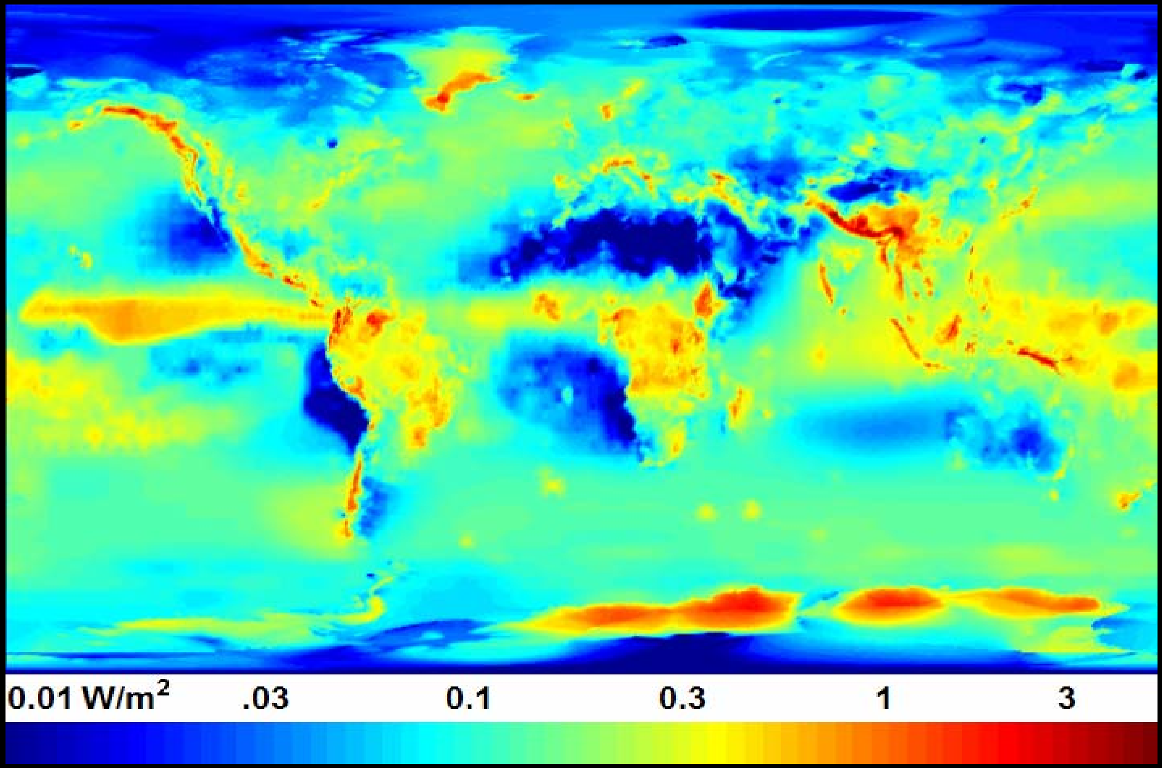


W. Hermann. Quantifying Global Exergy Resources. Energy 2006;31(12):1349-1366.

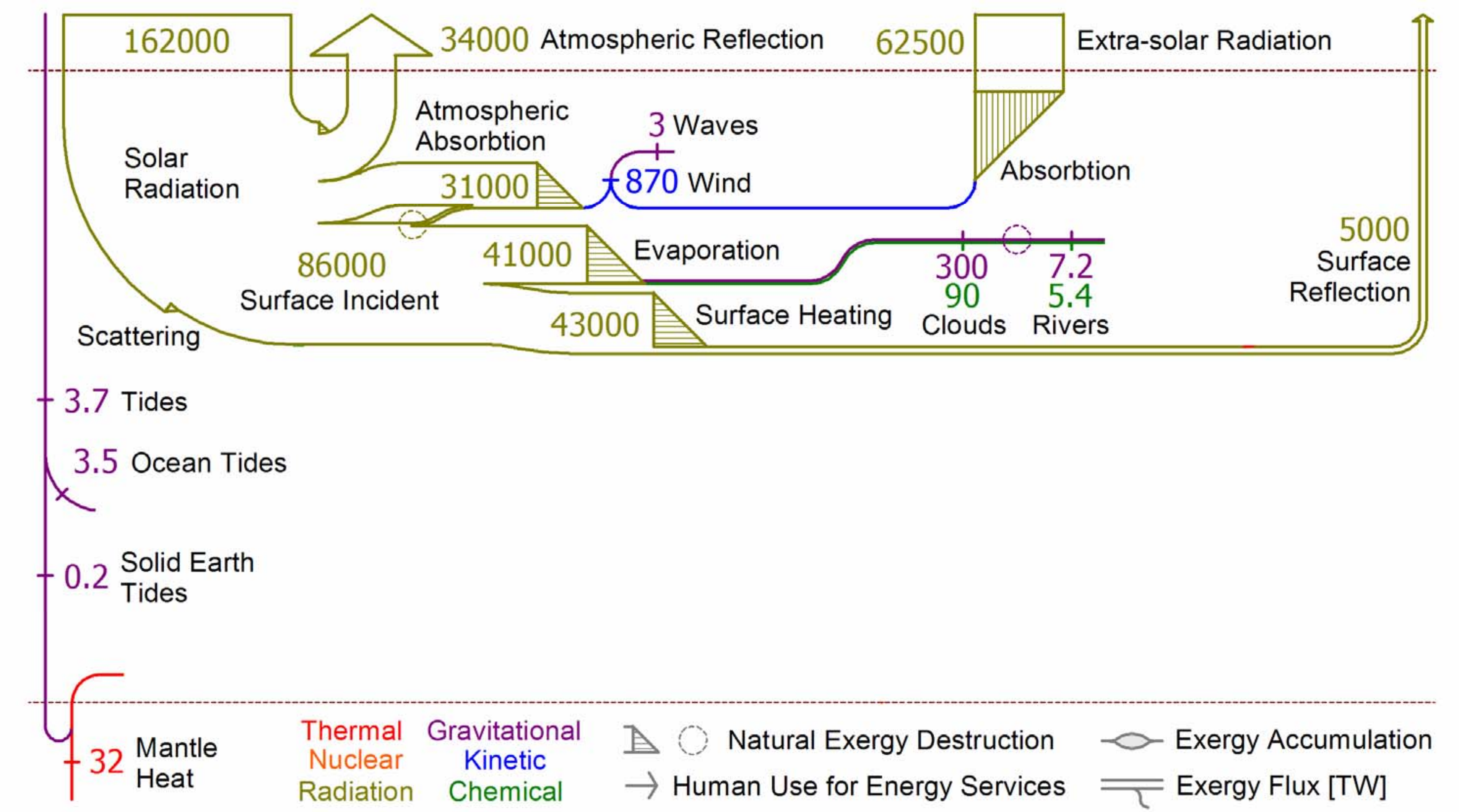
Precipitation

- Average precipitation is 18 Tg/s.
- Total flux is 25 TW gravitational and 19 TW chemical.
- Global average specific gravitational exergy is 6.6 kJ/kg and specific chemical exergy is 4.9 kJ/kg.



Legates DR, Wilmont CJ. NASA GSFC 2005; GLOBE Project, NOAA NGDC 2005

Exergy flux, accumulation, destruction, and use



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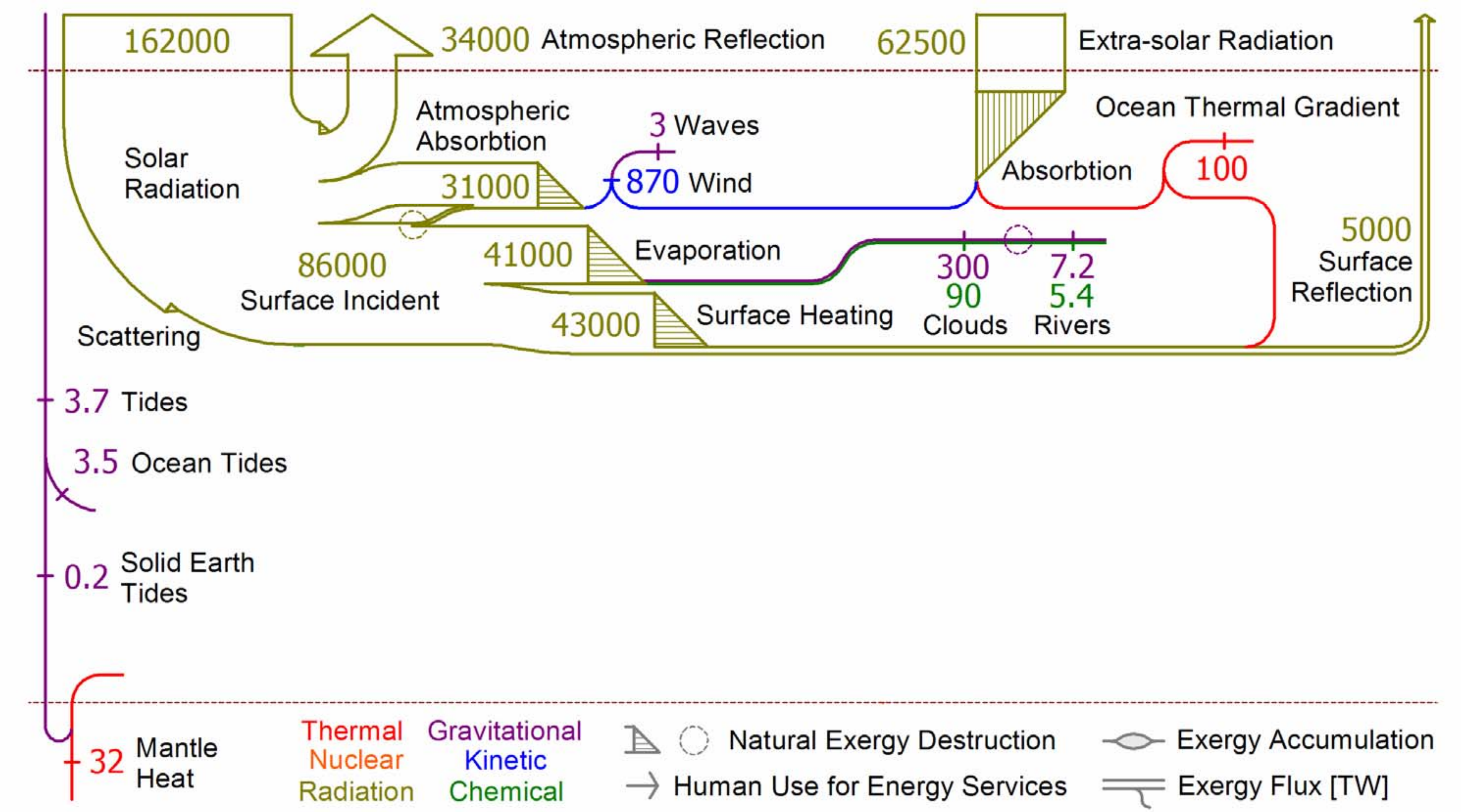
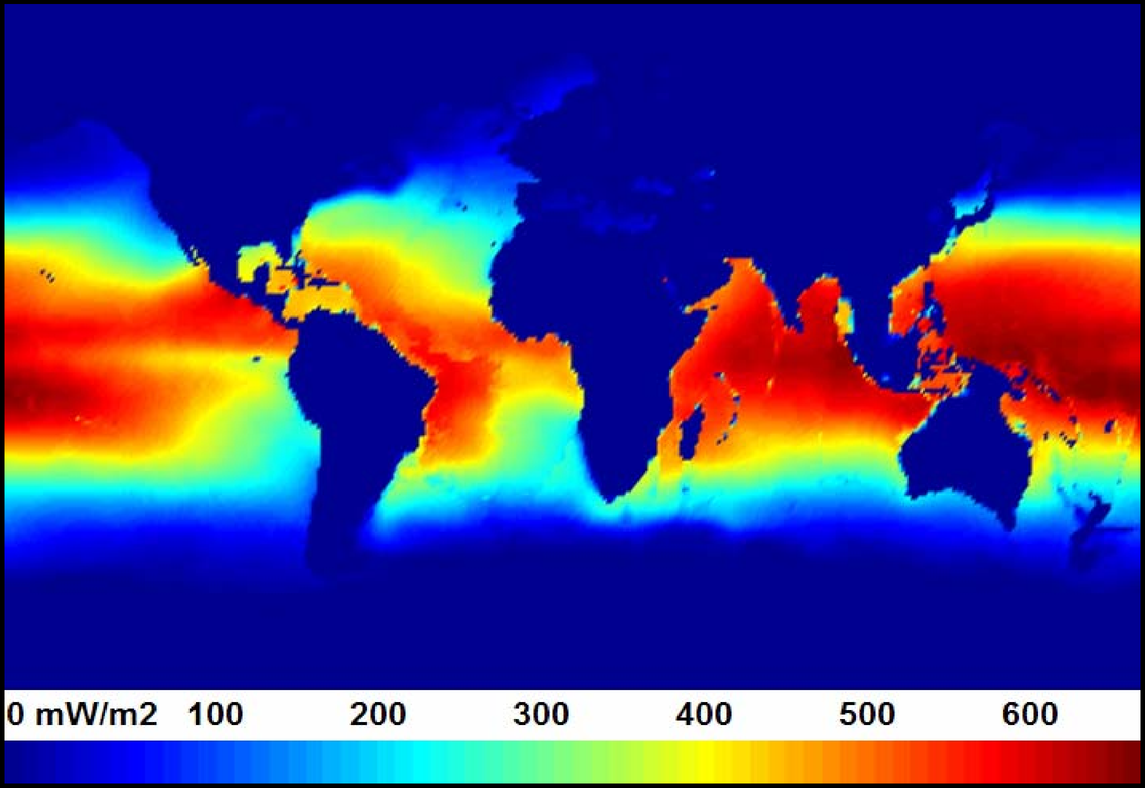


W. Hermann. Quantifying Global Exergy Resources. Energy 2006;31(12):1349-1366.

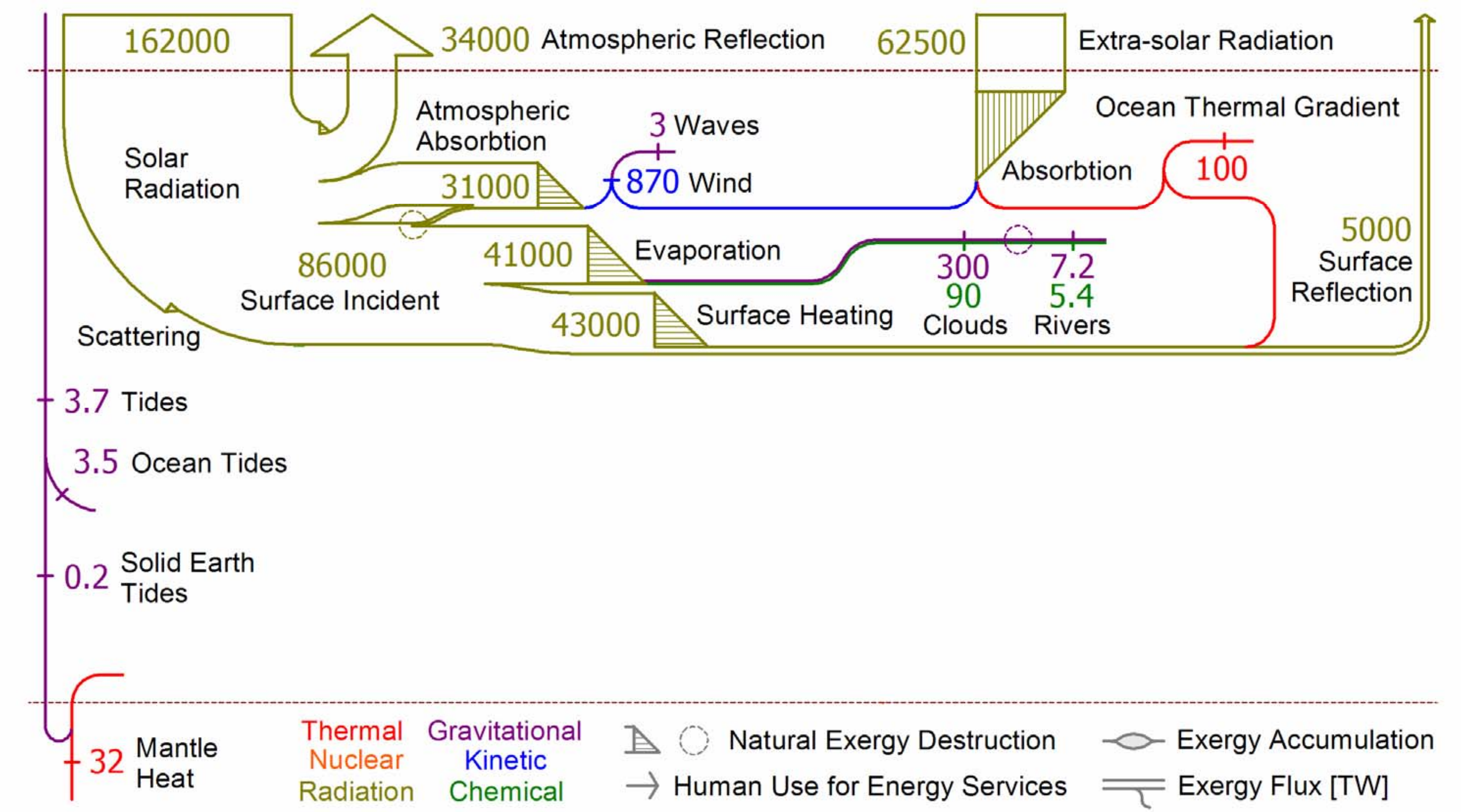
Ocean thermal gradient

- Energy transport in the THC is 2000 TW, but it is only 5% available (Q = 0.05) with a 20 K temperature difference. Large-scale use may destabilize transport.
- Specific thermal exergy is 800 J/kg.



World Ocean Database 2001, NOAA-NESDIS.

Exergy flux, accumulation, destruction, and use



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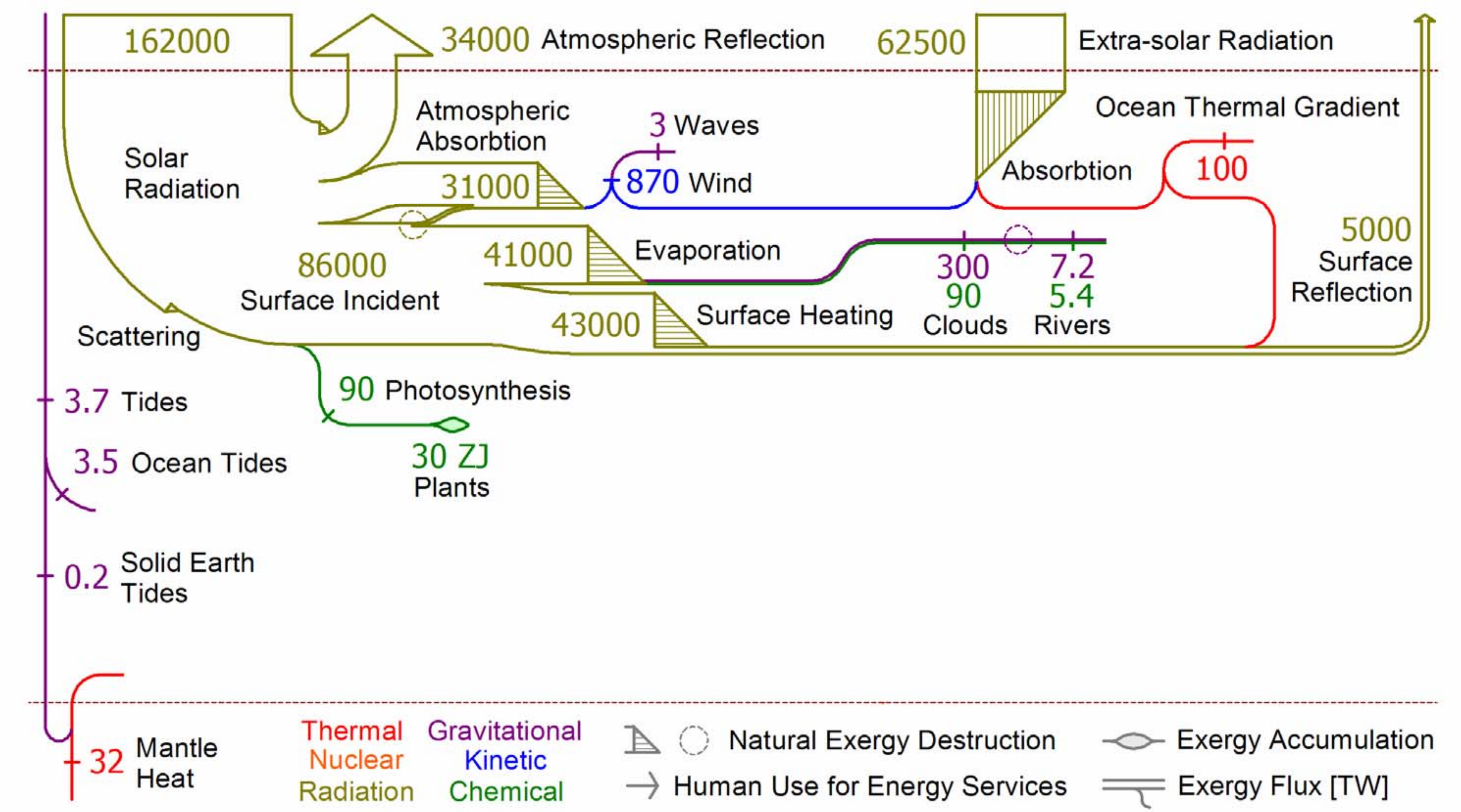

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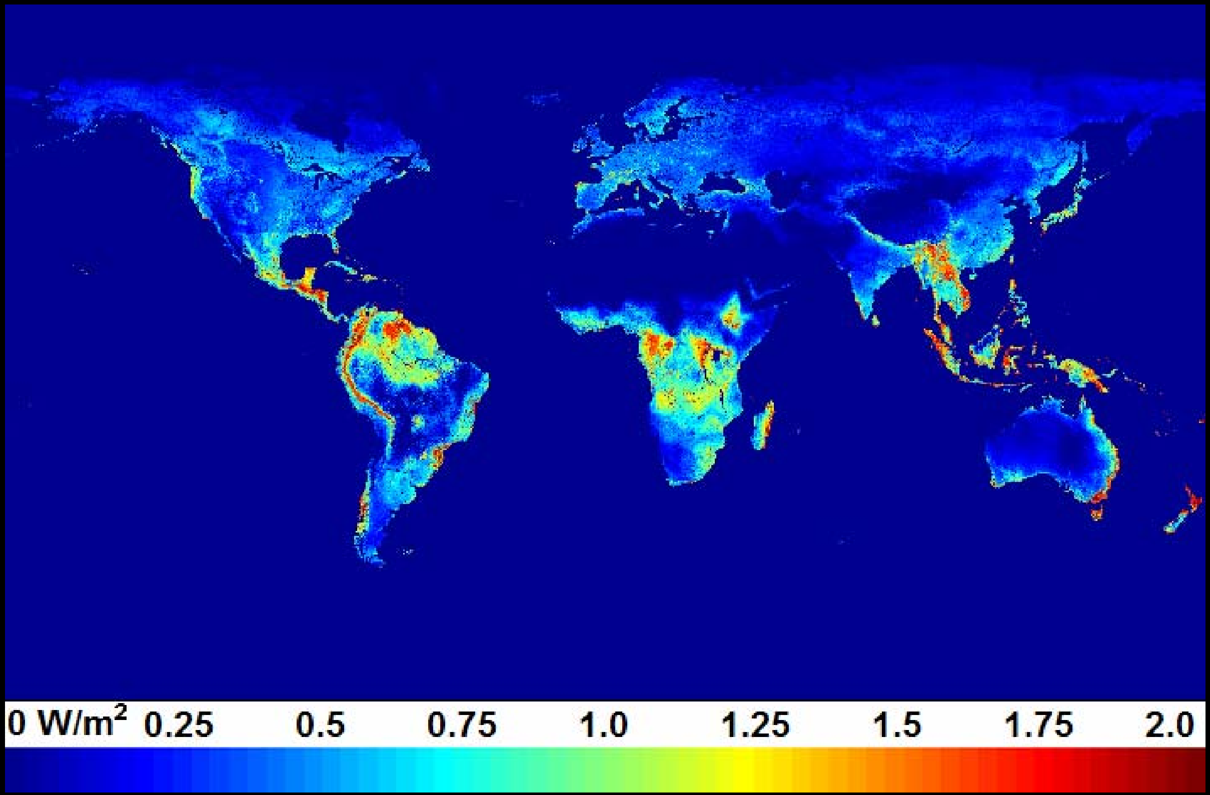
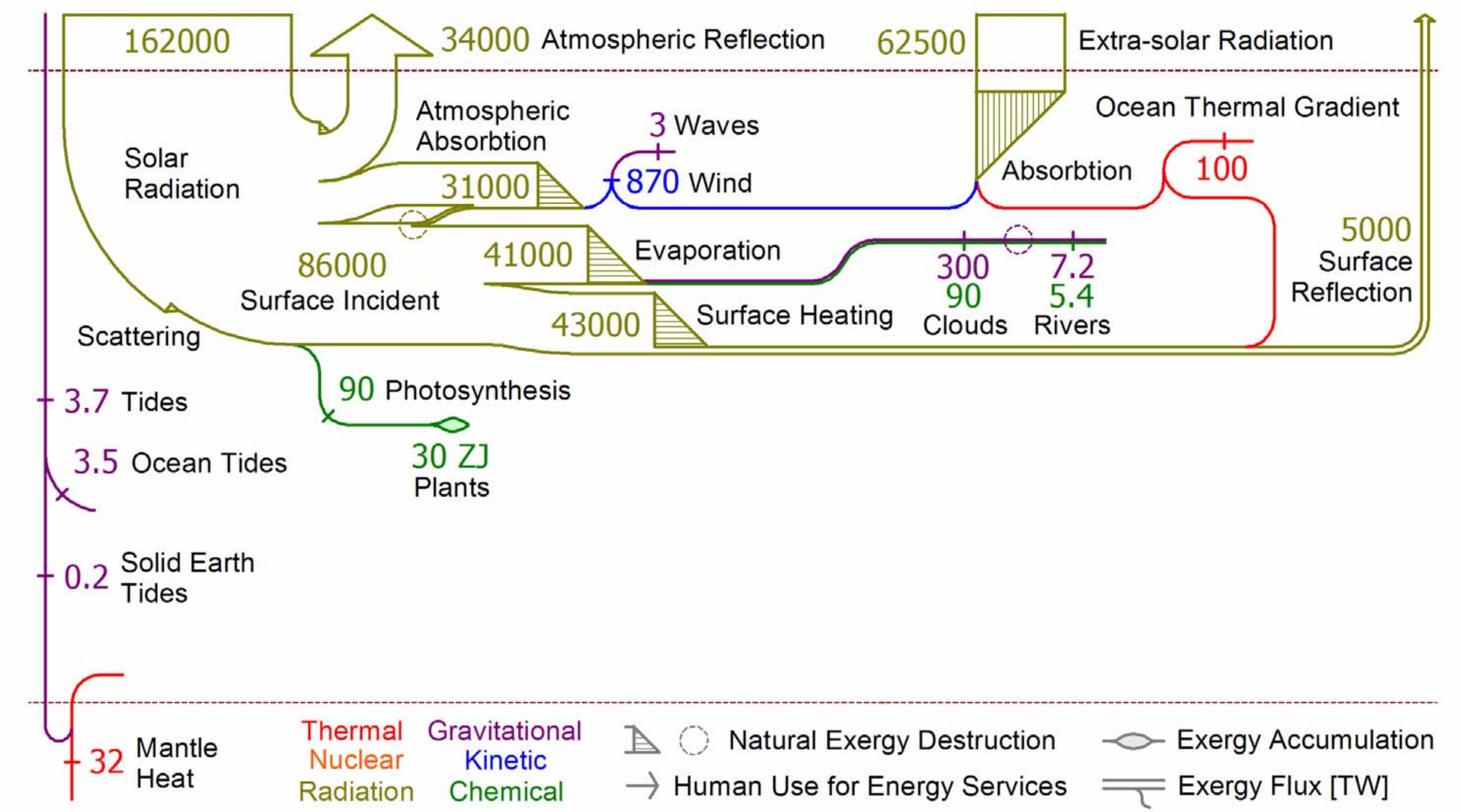
Photosynthesis

- 65 TW land (below) and 25 TW ocean productivity.
- Land residence time is 10 years, ocean is 1 month.
- Solar to plant matter efficiency is about 0.5-1%.
- Plant specific chemical exergy is 12-20 MJ/kg.



MODIS TERRA, NASA GSFC, JPL, LRC.

Exergy flux, accumulation, destruction, and use



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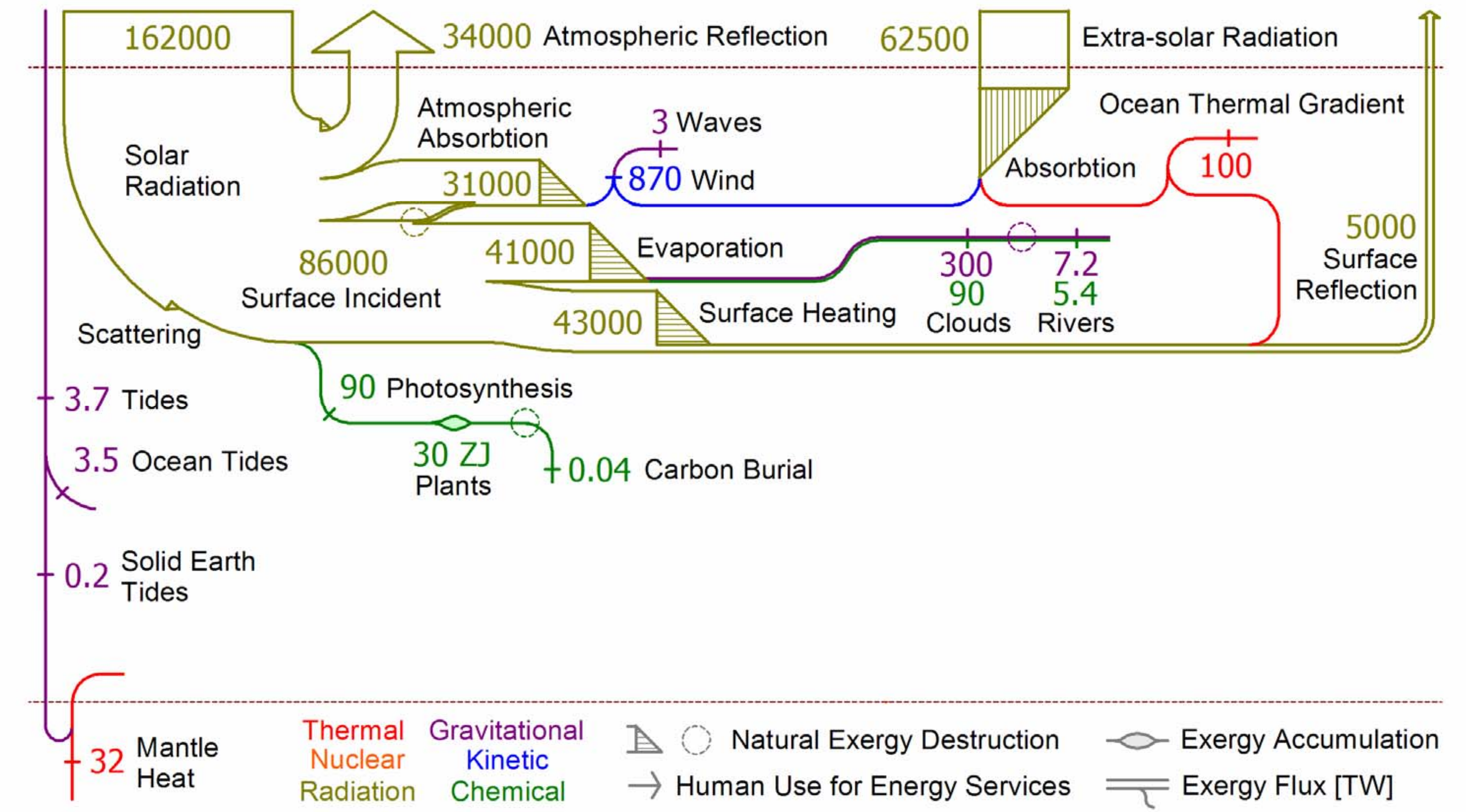

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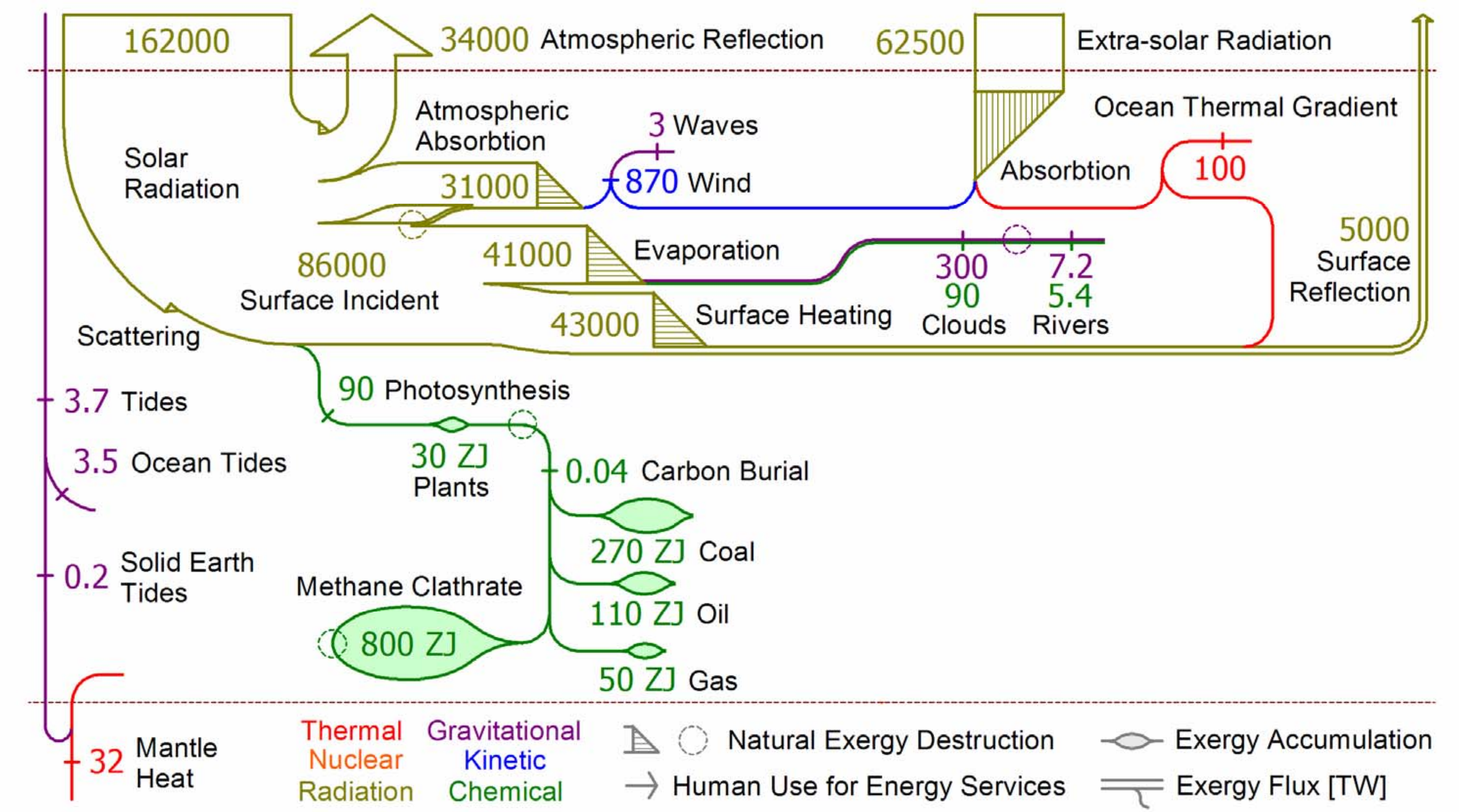

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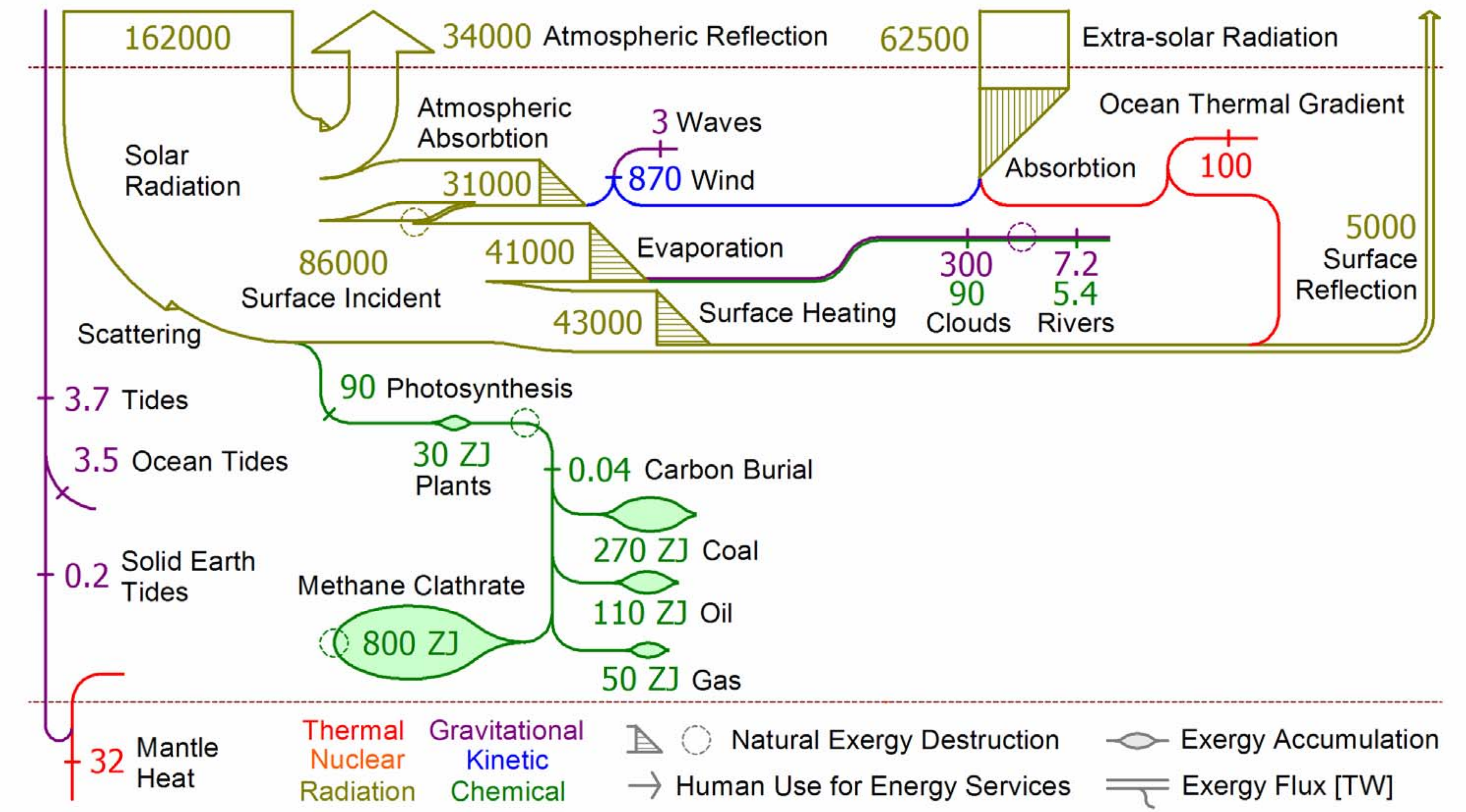
Fossil fuels

- Coal
  - Pulverizable solid, wide variety of grades.
  - 20-30 MJ/kg calculated with statistical correlations.
- Petroleum
  - 10 ZJ conventional, 100 ZJ unconventional resources.
  - Conventional and heavy oil 40-44 MJ/kg. Tar sands and oil shale 40 MJ/kg organic portion, 5-15 MJ/kg total.
- Natural gas
  - Lowest carbon intensity.
  - 50 MJ/kg.
- Methane clathrate
  - Methane-containing ice, narrow stability window.
  - 5 MJ/kg, 85% water, 15% methane and trace gases.

Exergy flux, accumulation, destruction, and use



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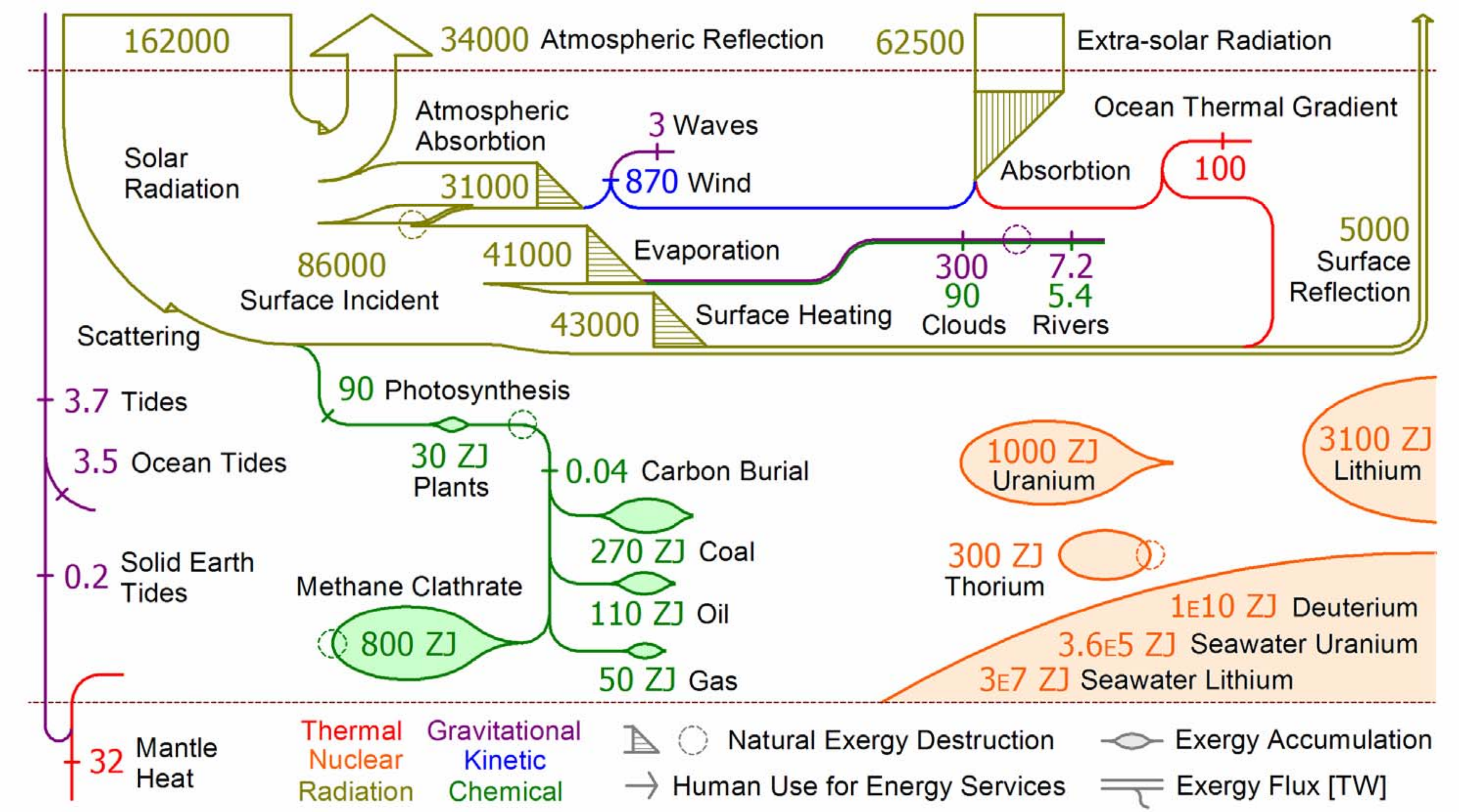
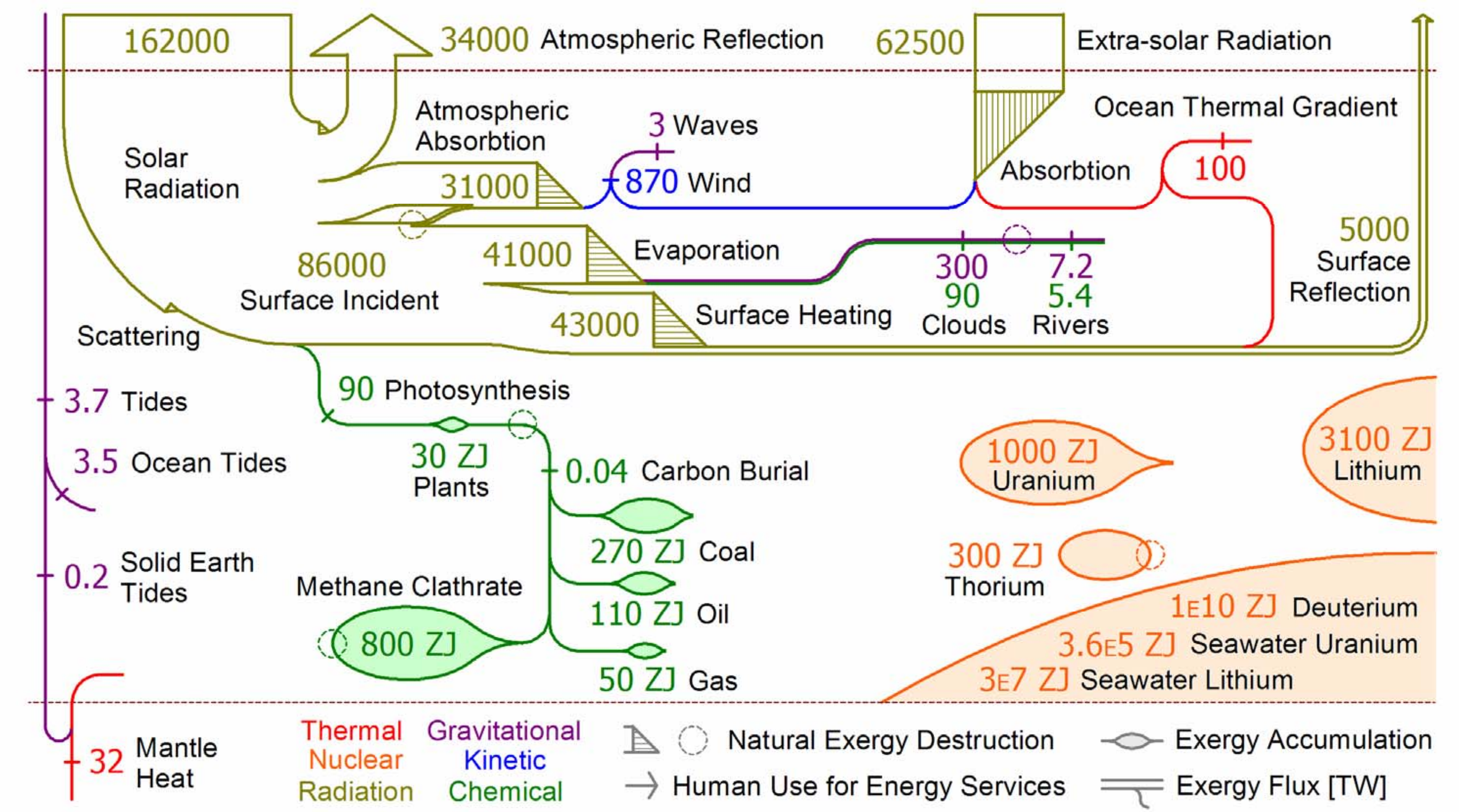


W. Hermann. Quantifying Global Exergy Resources. Energy 2006;31(12):1349-1366.

Nuclear materials

- Uranium 235 and 238
  - U-238 requires transmutation to Pu-239 with fast neutrons.
  - Specific exergy 77 TJ/kg.
- Thorium 232
  - Requires transmutation to U-233 with fast neutrons.
  - Specific exergy 78 TJ/kg.
- Lithium: tritium-deuterium fusion
  - Tritium is produced from lithium using neutrons.
  - Li-6 is less common than Li-7 but requires much less energy.
  - Specific exergy 226 TJ/kg.
- Deuterium-deuterium fusion
  - 1 in 5000 hydrogen atoms.
  - Ocean contains 1e31 J, on the order of the primary resources.
  - Specific exergy 345 TJ/kg.

Exergy flux, accumulation, destruction, and use



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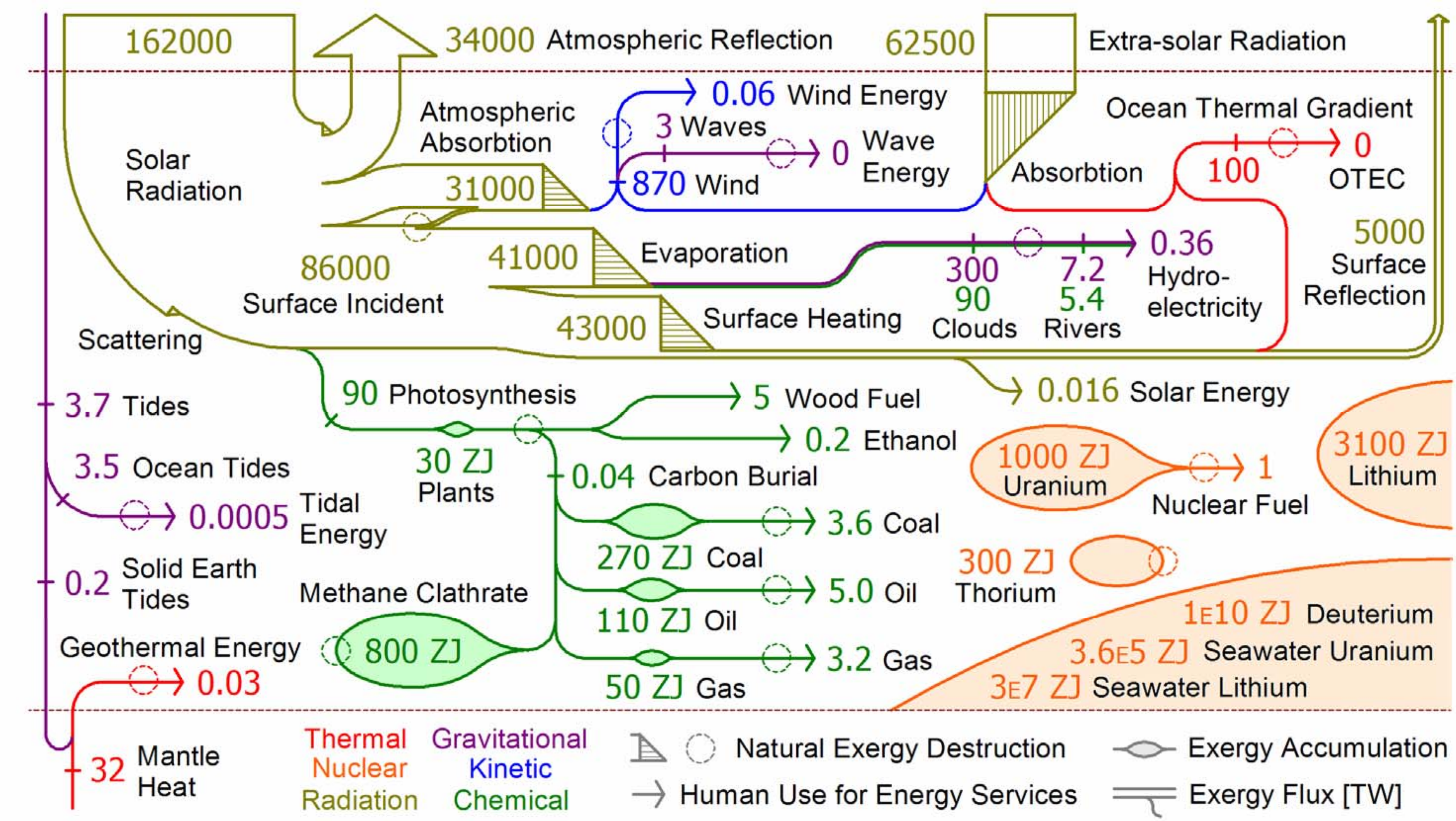
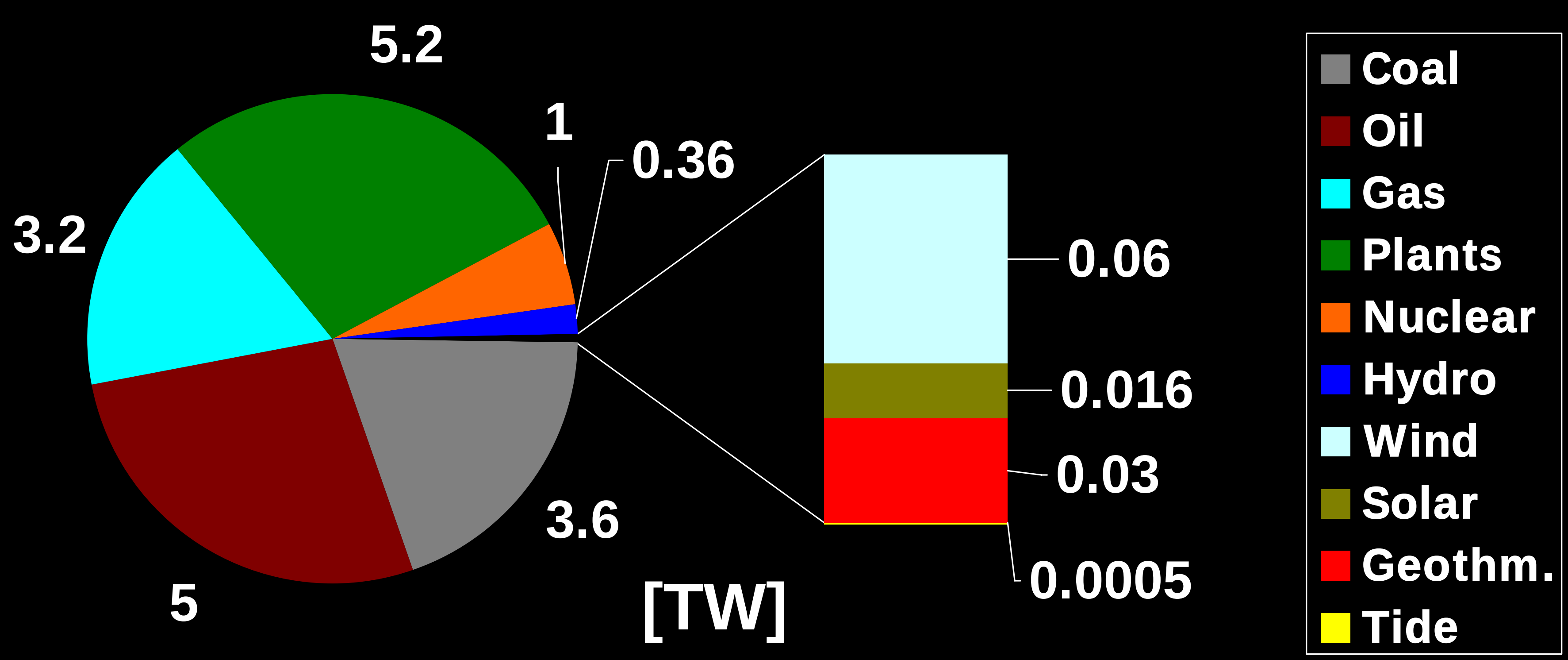


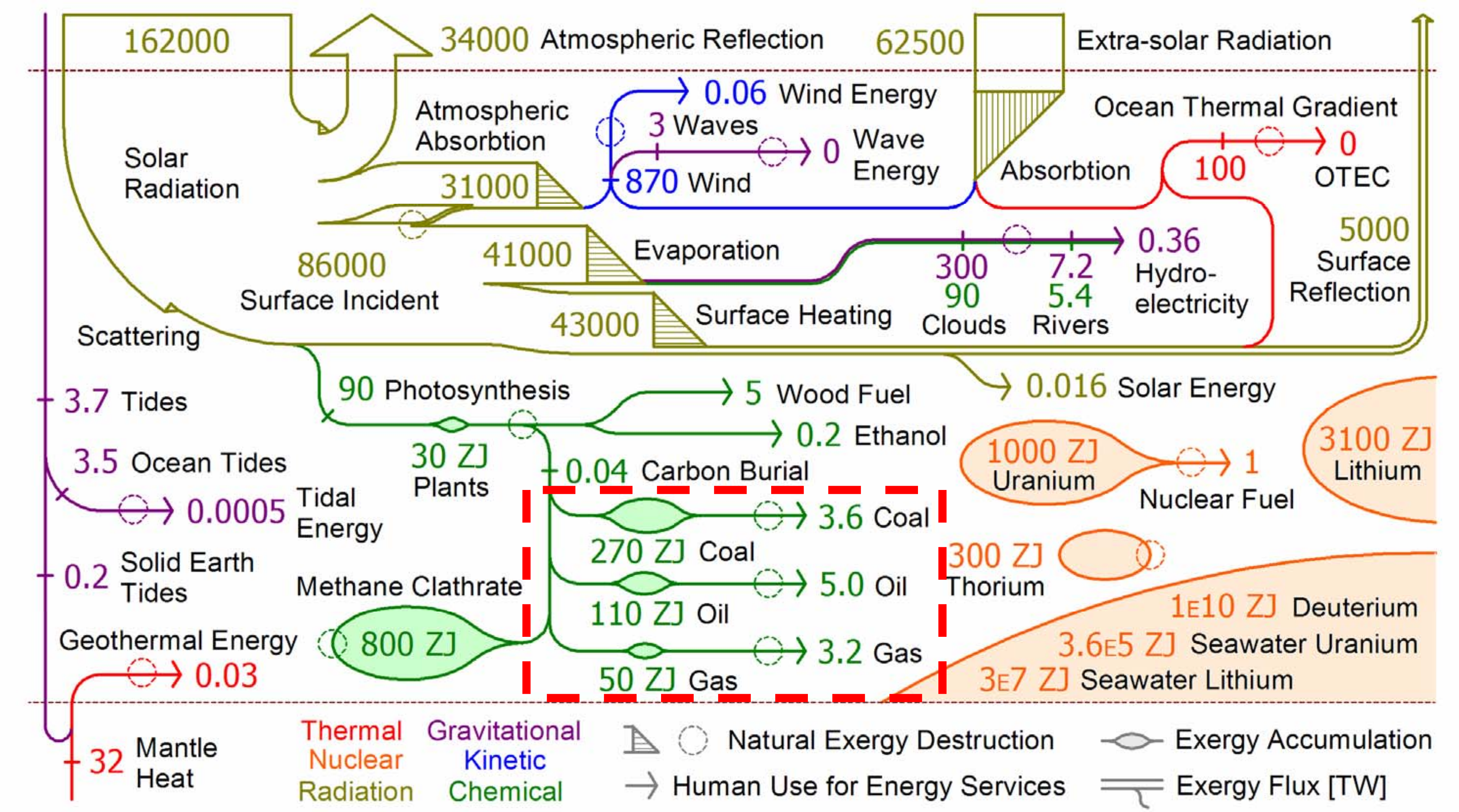
W. Hermann. Quantifying Global Exergy Resources. Energy 2006;31(12):1349-1366.

Exergy destruction for energy services

- 18 TW global exergy use.
- Global use is more than half the mantle heat exergy flux and 1/4800th of the surface incident solar radiation.
- Fossil fuels comprise 65% of exergy use.



Exergy flux, accumulation, destruction, and use



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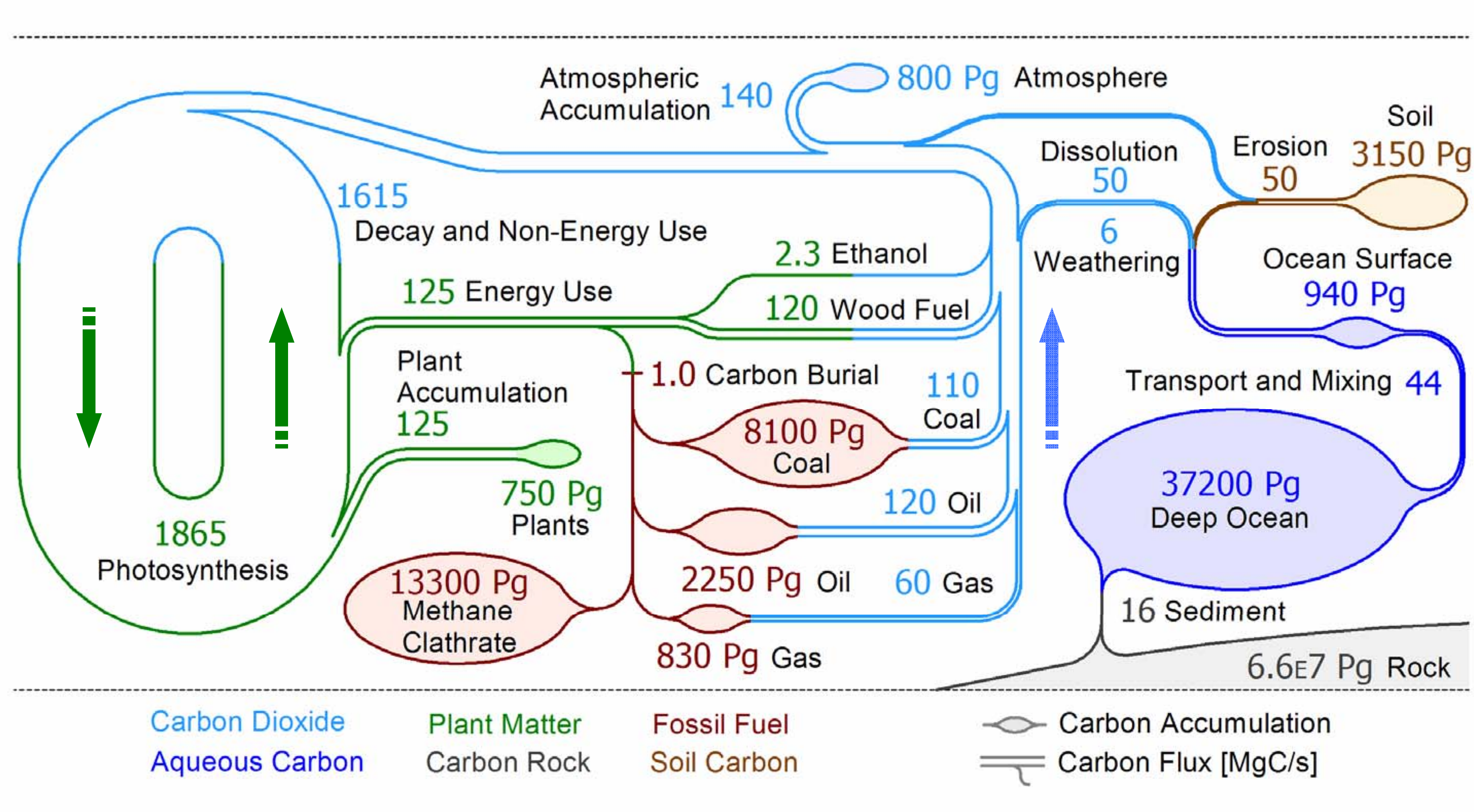
Carbon flow in the biosphere



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SCOPE 62 The Global Carbon Cycle. C.B. Field & M. Raupach (eds.), 2004, Island Press.

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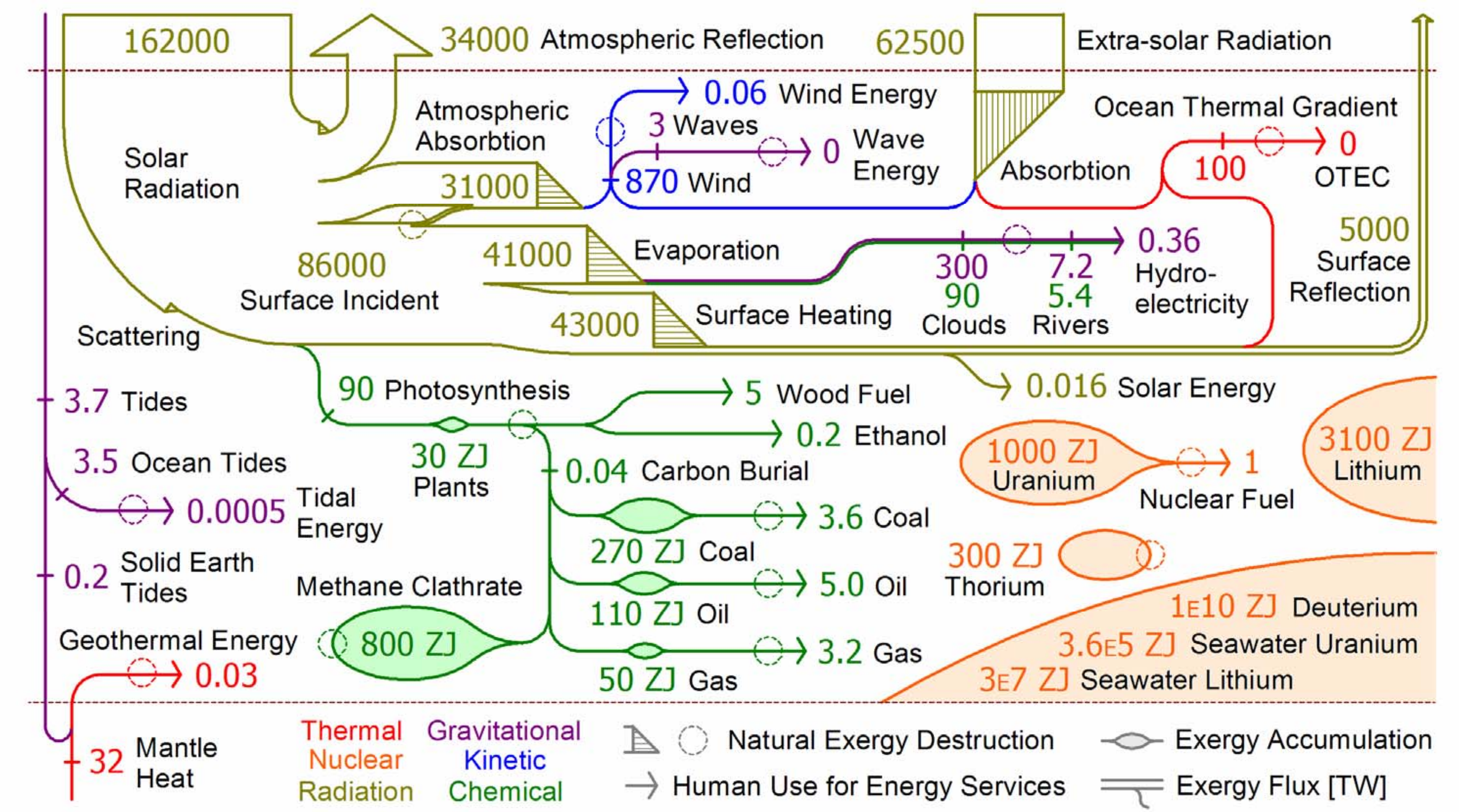

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Questions?