Earth's Exergy Resources
Energy Quality, Flow, and Accumulation in the Natural World

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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.
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.
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?
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 1\textsuperscript{st} and 2\textsuperscript{nd} laws of thermodynamics: “energy is conserved” and “things fall apart”.
- Energy quality is the ratio of exergy to energy. 
  \[ Q = \frac{X}{E} \quad \text{or} \quad \text{Exergy} = Q \times \text{Energy} \]
- 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.  
  \[ 100 \text{ J} \times 0.3 = 30 \text{ J} \]
- 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

\[ Q = 1 - \frac{T_o}{T} \]

- Liquid nitrogen
- LNG
- Geothermal
- Freezer air
- Warm air
- Turbine steam
- Combustion

\[ T_o = 289 \text{ K} \]
\[ Q = 1 - \frac{4T_o}{3T} + \left(\frac{T_o}{T}\right)^{4/3} \]

- Galactic radiation (2.7 K): \( Q \sim 10^6 \)
- Space heater: \( Q \sim 0.93 \)
- Hot water radiator
- Solar radiation: \( Q \sim 0.93 \)

\( T_o = 289 \text{ K} \)
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

<table>
<thead>
<tr>
<th>Chemical name</th>
<th>Bond potential [MJ/kg]</th>
<th>“DOF” potential</th>
<th>Diffusive potential</th>
<th>Chemical exergy [MJ/kg]</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>50.0</td>
<td>-0.1</td>
<td>2.0</td>
<td>51.9</td>
<td>1.037</td>
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<td>Octane</td>
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<td>1.3</td>
<td>1.5</td>
<td>47.5</td>
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<td>Ethanol</td>
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<td>0.8</td>
<td>1.1</td>
<td>29.6</td>
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<td>Acetylene</td>
<td>48.3</td>
<td>-1.2</td>
<td>1.6</td>
<td>48.7</td>
<td>1.008</td>
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<td>Hydrogen</td>
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<td>5.6</td>
<td>117.2</td>
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<tr>
<td>Aluminum</td>
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<td>-0.8</td>
<td>2.7</td>
<td>32.9</td>
<td>1.061</td>
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<tr>
<td>Freshwater</td>
<td>0</td>
<td>0</td>
<td>0.0049</td>
<td>0.0049</td>
<td>n/a</td>
</tr>
</tbody>
</table>
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?
Primary exergy resources

Solar radiation

Galactic Radiation (2.7 K)

Lunar gravitation

Core heat

Earth rotational KE: 5e29 J
Earth core heat flux: 2e31 J
Earth incident radiation: 5.5e34 J

Exergy flux, accumulation, destruction, and use

Exergy flux, accumulation, destruction, and use

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 m² of ocean surface and m of tidal range.
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 $Q \approx 0.7$ at 40 km deep, exergy flow is 32 TW.
Exergy flux, accumulation, destruction, and use

Solar Radiation

Tides

Ocean Tides

Solid Earth Tides

Mantle Heat

Thermal Nuclear Radiation

Gravitational Kinetic Chemical

Natural Exergy Destruction

Human Use for Energy Services

Exergy Accumulation

Exergy Flux [TW]

Exergy flux, accumulation, destruction, and use

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.

Exergy flux, accumulation, destruction, and use

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.
Exergy flux, accumulation, destruction, and use

Exergy flux, accumulation, destruction, and use

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.
Exergy flux, accumulation, destruction, and use

Exergy flux, accumulation, destruction, and use

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.
Exergy flux, accumulation, destruction, and use

Exergy flux, accumulation, destruction, and use

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.
Exergy flux, accumulation, destruction, and use

Exergy flux, accumulation, destruction, and use

Exergy flux, accumulation, destruction, and use

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

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

Exergy flux, accumulation, destruction, and use

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

Exergy flux, accumulation, destruction, and use

Questions?