EARTH’S ANNUAL ENERGY BUDGET (ECOLOGY)

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Life pivots completely on energy. We cannot talk about living beings without considering the interchanges of energy that they make with their environment. If these interchanges did not take place or if a source of energy like our Sun did not exist, the living beings on Earth would not exist either. Consequently, biologists must thoroughly understand the ways by which our planet acquires energy, the amount of energy that it receives in a given period of time, annual balance of that energy in different Earth subsystems and how living beings can take advantage of such energy.

The following article is a summary of the amount of energy that receives our planet from the Sun (See Figure 3), its magnitudes and of how it is distributed in the terrestrial system.

I have included the amount of incident solar energy upon each planet and the planetoid Pluto so that you have an idea of the privileged situation of our planet in the neighborhood of the Solar System.
AMOUNT OF INCIDENT SOLAR RADIATION UPON EACH PLANET

Formula:

\[ G_{PL} = \frac{Q_{\odot}}{4\pi (P_{OR})^2} \]

Where,

\( G_{PL} \) is the amount of incident solar radiation upon the planet.

\( Q_{\odot} \) is the bolometric total solar irradiance from the Sun expressed in Watts (3.94832e+26 W).

\( 4\pi = 12.56637061 \)

\( P_{OR} \) is the Planetary Orbital Radius, expressed in meters.

TOTAL INCIDENT ENERGY UPON EACH PLANET:

Mercury = 9449.43 W/m^2

Venus = 2687.6 W/m^2

Earth = 1402.8 W/m^2

Mars = 612.55 W/m^2

Jupiter = 52.34 W/m^2

Saturn = 17.2 W/m^2

Uranus = 3.89 W/m^2

Neptune = 1.55 W/m^2

Pluto (Planetoid) = 0.8998 W/m^2

Average of incident solar energy upon Earth during Aphelion = 1359.02 W/m^2

Average of incident solar energy upon Earth during Perihelion = 1452.77 W/m^2
**EARTH’S ANNUAL ENERGY BUDGET**

1365 W/m^2 is the annual average of total solar radiation measured by satellites on Top Of the Atmosphere (TOA). [4]

682.64 W/m^2 are thermal radiation impinging on TOA.

\[ R_{atm} \rightarrow 136.528 \text{ W/m}^2 (20\%) \] are reflected by the atmosphere, especially by clouds and dust.

136.528 W/m^2 (20%) are absorbed directly by the atmosphere, in particular by ozone, clouds and dust.

\[ S_{atm} \rightarrow 40.958 \text{ W/m}^2 (6\%) \] are scattered by molecular oxygen and nitrogen at the upper atmosphere.

After mitigation by the atmosphere, the thermal radiation impinging on the surface is:

\[ \text{Insolation} = 682.64 \text{ W/m}^2 - 136.528 \text{ W/m}^2 - 136.528 \text{ W/m}^2 - 40.958 \text{ W/m}^2 = 368.626 \text{ W/m}^2. \]

From 368.626 W/m^2, the surface reflects 25.8 W/m^2 (7%).

342.8 W/m^2 are received on Earth’s surface, which is formed by the cryosphere (snow and ice), the lithosphere (land), the hydrosphere (oceans) and the biosphere (living beings).

From the solar thermal radiation received, the surface (land and oceans) absorbs 239.96 W/m^2.

A - Total of solar thermal radiation lost directly into space before it hits on the surface:

\[ R_{atm} + S_{atm} = 177.5 \text{ W/m}^2. \]

B - 136.528 W/m^2 (19.9%) are absorbed directly by the atmosphere.

C - Total of solar thermal radiation impinging on the surface after mitigation = 368.626 W/m^2.

Total ThR impinging on TOA = A + B + C = 177.486 W + 136.51 W + 368.626 W = 682.64 W/m^2

Total received on the surface = 343 W/m^2.

Total absorbed by the surface = 240 W/m^2.

**BALANCE OF ENERGY ABSORBED AND EMITTED BY THE SURFACE:**

Total solar thermal radiation absorbed by the surface = 240 W/m^2.

Per each 100 W/m^2, the surface emits:

Sensible Heat Flux = 12%. 


Latent Heat of Evaporation = 48%
Directly lost to outer space = 12%
Transferred to the atmosphere by radiation = 14%
Dissipated as dynamic energy in sinks: 14%. [3]

Therefore:

From 240 W/m^2 of thermal energy absorbed, the surface emits:

D - Sensible Heat Flux (Convective Heat Transfer): 28.8 W/m^2.
E - Emitted by the surface to the atmosphere as latent heat of evaporation: 115.2 W/m^2.
F - Emitted by the surface directly to the outer space: 28.8 W/m^2.
G - Transferred to the atmosphere by radiation: 33.6 W/m^2.
H – Dissipated as dynamic energy in sinks: 33.6 W/m^2.

The remainder 103 W/m^2 are distributed as follows:

I - 98.7% are transferred to subsurface materials (by conduction and convection) and is transformed into unusable internal and potential energy of atmosphere, hydrosphere, biosphere, cryosphere, and lithosphere: 101.661 W/m^2. (Peixoto and Oort, 1992)

J - 0.8 % is absorbed by autotrophic stratum (biosphere): 0.824 W/m^2

K - 0.5% is transferred to currents and waves (thermal kinetic energy): 0.515 W/m^2

Consequently, net thermal radiation emitted by the surface is:

\[
ThRs = D + E + F + G + H + I + J + K \\
= 28.8 W + 115.2 W + 28.8 W + 33.6 W + 33.6 W + 101.661 W \\
+ 0.824 W + 0.515 W = 343 W
\]

This energy is lost into the outer space; as a rule, it is emitted during nighttime, or it is compensated by gravity field.

If environmental adiabatic lapse rate ($\lambda$) is lower than dry adiabatic lapse rate ($\lambda_d$), the equilibrium will be stable. If both environmental and dry adiabatic lapse rates are identical, static equilibrium will be neutral. If $\lambda$ is higher than $\lambda_d$, static equilibrium will be unstable. [3]

The later happened during my last experiment, so the phenomenon is observable. If the surrounding parcels of air are not in hydrostatic equilibrium, the air parcel’s static stability will turn chaotic. The latter often happens with climate; that’s why climate science is plenty of physics errors and misinterpretations.
**Summary from previous section:**

- Bolometric Solar Irradiance is only mitigated by distance on its way towards the Earth. An amount of Solar Irradiance is mitigated by interplanetary dust and the Sun’s gravity field.

- The bolometric solar irradiance on TOA is approximately 1365 W/m$^2$.

- From the bolometric solar irradiance on TOA, 682.64 W/m$^2$ are thermal radiation, i.e. Energy that can be transferred as heat or work.

- After penetrating the Earth’s atmosphere, the solar thermal radiation is mitigated by absorption, scattering and reflection by the atmosphere before it strikes on the surface (biosphere, cryosphere, lithosphere and hydrosphere). As it strikes on the surface, part of the incident thermal radiation is reflected by the surface and incident thermal radiation decreases to 343 W/m$^2$.

- From incident thermal radiation of 343 W/m$^2$, the Earth’s surface absorbs ~240 W/m$^2$.

- Measurements on the hemisphere facing the Sun, at Zenith angle, give a Flux of Solar Power ($S$) on Earth’s surface of $\sim$1000 W/m$^2$, which is introduced to calculate local and regional insolation at a given hour of the day. Incident solar thermal radiation diminishes according to the angle of incidence.

- The formula to calculate insolation is $I = S \times (Z)$

  Where $I$ is for insolation, $S$ is for flux of solar power at Zenith angle that is 1000 W/m$^2$, and $Z$ is for Zenith angle obtained from considering latitude, solar angle of incidence and day hour.

**THERMAL EFFICIENCY AND DOWNWARD RADIATION FROM THE ATMOSPHERE**

The Kelvin-Planck formulation of the second law of thermodynamics states that it is impossible for a system to go through a cyclical process whose only effect is the heat flow towards the system from a warm reservoir and that the system renders an equivalent amount of work on the medium. [1]

In other words, the second law of thermodynamics establishes that no process in nature is 100% efficient. [2]

Another interpretation of the second law states that the heat always flows from higher energy density systems to lower energy density systems. [1, 2, 5, 6, and 7]
Heat is energy in transit, i.e. in the process of being transferred from a system to another system. For this cause, we conclude that heat is a process function (a process, not a state of a system). [1, 2, 5, 6, and 7]

However, heat can be transferred from one system to another system by three mechanisms, conduction, convection and radiation. [7]

When heat is transferred by radiation, we refer to it as thermal radiation or dynamic energy.

In the system surface-atmosphere, heat is transferred by the three mechanisms of heat transfer [3]; nevertheless, we will only refer to thermal radiation on this section.

Thermal efficiency coefficient is the ratio at which heat can be converted into work [1, 2, and 5]. Heat and work are irreversible processes in the real world. For this reason, the thermal efficiency coefficient (ε) of thermal radiation cannot be higher than 0.5.

**EXAMPLE**

The temperature of soil (dry clay) in a pot, whose surface is 1 m² and whose volume is 1 m³, at 16:30 hrs (CST) was 295.25 K, while the temperature of the atmosphere was 297.35 K. The thermal efficiency from the atmosphere to the soils was:

\[
\varepsilon = \frac{T_{\text{high}} - T_{\text{low}}}{T_{\text{high}}}
\]

Introducing magnitudes:

\[
\varepsilon = \frac{297.35 \text{ K} - 295.25 \text{ K}}{297.35 \text{ K}} = \frac{2.1 \text{ K}}{297.35 \text{ K}} = 0.0071
\]

Another equation to calculate the thermal efficiency coefficient is as follows:

\[
\varepsilon = 1 - \frac{T_{\text{low}}}{T_{\text{high}}}
\]

Introducing magnitudes:

\[
\varepsilon = 1 - \frac{295.25 \text{ K}}{297.35 \text{ K}} = 1 - 0.99294 = 0.0071
\]

From this example we see that thermal radiation transfer happens from the atmosphere to the pot with an efficiency of 0.0071, or 0.71%. This means that the thermal radiation from the
atmosphere converted into usable thermal potential energy or any other form of usable thermal energy which is stored by dry clay in the pot is 0.71%.

Thermal radiation is absolutely dependent on temperature; therefore, the thermal radiation emitted by the atmosphere and absorbed by the pot would be:

\[
q/A = 0.201 \times \left( \frac{5.6697 \times 10^{-8}}{W/m^2 K^4} \right) \times \left( (295.25 K)^4 - (297.35 K)^4 \right) = -2.49 W/m^2
\]

The minus sign means that the transfer of heat happens from the surroundings to the surface because the atmosphere is warmer than the dry clay in the pot. 0.201 is the average emittance of the atmosphere. Consequently, the thermal radiation from the air to the dry clay in the pot is 2.49 W/m².

Given that clay has an absorptivity limit, which is around 0.65, the absorbed thermal radiation from the atmosphere is 2.49 W/m² * 0.65 = 1.62 W/m².

From 1.62 W/m², the thermal radiation convertible to work, i.e. usable thermal energy is

\[
\left( \frac{1.62 W}{m^2} \right) \times 0.0071 = 0.0115 \frac{W}{m^2}
\]

Solving for \(q\):

\[
q = 1 m^2 \left( 0.0115 \frac{W}{m^2} \right) = 0.0115 W
\]

As the total process takes one second, the energy implied in the process is:

\[
E = (0.0115 W \times 1 s) \left( \frac{J}{W \times s} \right) = \frac{0.0115 (W s) J}{(W s)} = 0.0115 J
\]

And the change of temperature of dry clay caused by 0.0115 W is:

\[
\Delta T_{clay} = \frac{E}{m \times Cp} = \frac{(0.0115 J)}{\left( 1.2 kg \times 1000 \frac{J}{kg \cdot K} \right)} = 9.6 \times 10^{-6} K
\]

Evidently, the effect of downward radiation is negligible.

**THERMAL RADIATION BETWEEN THE ATMOSPHERE AND THE SURFACE.**

On this topic, we will consider only the lower troposphere layer conformed by the volume of air with length of 3 km altitude.
From calculations of the global energy budget, we found the solar power absorbed by the atmosphere was 136.53 W/m^2.

To this amount of solar power, which is transformed into static energy, we add the thermal radiation emitted from the surface which is absorbed by the air, the convective power flux from the surface to the atmosphere, the latent heat of evaporation from the surface and the thermal radiation emitted from the surface which is absorbed by the atmosphere. We obtain the following total amount of power flux:

\[ Q_{\text{atmos}} = 136.53 \text{ W/m}^2 + 28.8 \text{ W/m}^2 + 115.2 \text{ W/m}^2 + 33.6 \text{ W/m}^2 = 314.13 \text{ W/m}^2 \]

Given that the total amount of thermal energy contained by the surface is 240 W/m^2, we find that the atmosphere contains a higher amount of thermal energy than the surface. However, not all this energy is radiated towards the surface, but only 67% from it because the main part is transformed into unusable stationary energy. So that, the total amount emitted from the atmosphere towards the surface is:

\[ 314.13 \text{ W/m}^2 \times 0.67 = 63.14 \text{ W/m}^2 \]

This value coincides with the measurements taken during my first experiment on downward radiation from the atmosphere towards the surface. [8]

From this amount, the surface absorbs 44.2 W/m^2, which would cause a change of temperature of the surface of 0.000025 K.

Nevertheless, the correct procedure to calculate the net rate of thermal radiation exchange between the surface and the atmosphere is by using the following formula:

\[ Q_{\text{net}}/A = (\sigma \left(T_w^4 - T_c^4\right)) / ((1/\epsilon_w) + (1/\epsilon_c) - 1) \]

For the case of a surface at 310 K and an atmosphere at 298 K, the net rate of thermal radiation exchange is:

\[ Q_{\text{net}}/A = ((5.6697 \times 10^{-8} \text{ W/m}^2 \text{ K}^4) \times ((310 \text{ K})^4 - (298 \text{ K})^4)) / ((1/0.65) + (1/0.201) - 1) \]

\[ Q_{\text{net}}/A = (76.5 \text{ W/m}^2)/5.51 = 13.87 \text{ W/m}^2. \]

13.87 W/m^2 is the amount of thermal radiation exchanged by the atmosphere and the surface in both directions, under such conditions of temperature, from and to surface areas of one square meter, each second.

13.87 W/m^2 would cause a change of temperature of the surface of 0.000008 K, while the change of temperature of the air for this loss of energy would be -0.24 K.

Complexity appears as there are more than two surfaces partially or totally facing whether it be towards the surface or towards the atmosphere. In such cases we have to make use of another formula integrating the flux from each one of the surfaces. At any rate, the emitter will be always the warmer surface and the absorbers will be always the cooler surfaces.
Dampened clay shows a particularity because its temperature remains constant, at least during nighttime. On this situation, the net rate of thermal radiation flux is inversely proportional to the temperature of the atmosphere. If temperature of clay decreases with time, the correlation is proportional, but not linear.

The following graph shows the conditions of dampened clay (Figure 1):

Figure 1. Net Rate of Thermal Radiation Flux from Dampened Soil to Air. The correlation between Net Fluxes of Thermal Radiation from soil to atmosphere is inversely proportional to atmospheric temperature (Measurements of atmospheric temperature were made with pyrometers).
Illustration about incoming solar thermal energy to Earth.

- Insolation or Incident Solar Irradiance on Earth's Surface
- Total Solar Radiation on TOA = ~1365 W/m²
- Bolometric Solar Radiation on TOA = ~1365 W/m²
- Solar Thermal Radiation = ~950 W/m²
- Other Radiation = 691 W/m²
- Incident solar thermal radiation on Earth's surface, at Zenith angle = ~1000 W/m²

- Earth's Surface absorbs ~240 W/m² of solar thermal radiation
- Solar thermal radiation is scattered by absorption, scattering, and reflection by the atmosphere before it strikes on the surface (biosphere, cryosphere, atmosphere and hydrosphere).
- The Earth's surface absorbs ~240 W/m².
- Measurements on the hemispheres facing the Sun at Zenith angle, gives a Flux of Solar Power (S) on the Earth's surface is ~1000 W/m², which is introduced to calculate local and regional irradiation at a given hour of the day. Incident solar thermal radiation diminishes according to the angle of incidence.
- Formulas for calculated incident (S = 1000 W/m²) (2)
- Zenith angle obtained by considering latitude, solar angle of incidence and day/season.
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8. [http://www.biocab.org/Concise_Experiment_on_Backradiation.pdf](http://www.biocab.org/Concise_Experiment_on_Backradiation.pdf)