



Thanatia & Pristinia: Physics or Philosophy?

Antonio Valero | 16 October 2026

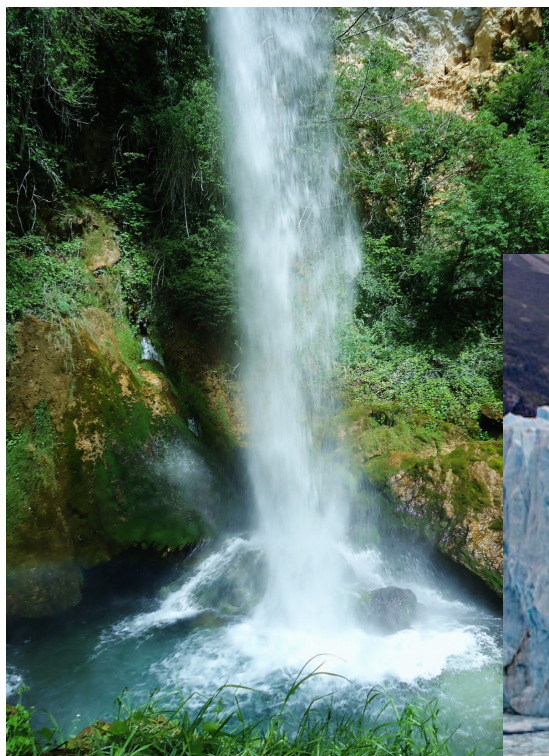
How Can Thermodynamics Help Manage Natural Resources?

- What kind of Natural Resources?
- Fossil Fuels, Biomass, Renewables?
- Energy, Raw Materials, Water, Fertile Soils, Ecosystems, the Atmosphere, the Hydrosphere, the Crust, the Anthroposphere, the Wasteworld, the Planet?
- Why not exergy?
- If the distinction from the commonness make things valuable, we need to define what properties make things unique and what is commonness. Both!

- What would be the Reference Environment?
- What would be the properties to characterize exergy?
- Would be exergy the best property to characterize the Raw Materials Value?

What Reference Environment?

- A river, a glacier, a mine... have exergy, but with respect to what?



Two States Are Needed to Assess a Mineral Resource

To calculate the exergy of a mineral in a mine we need two states (properties).

- 1) The concentration and composition of the mine
 - Concentration (Ore grade)
 - Composition
 - Amount (Tonnage)

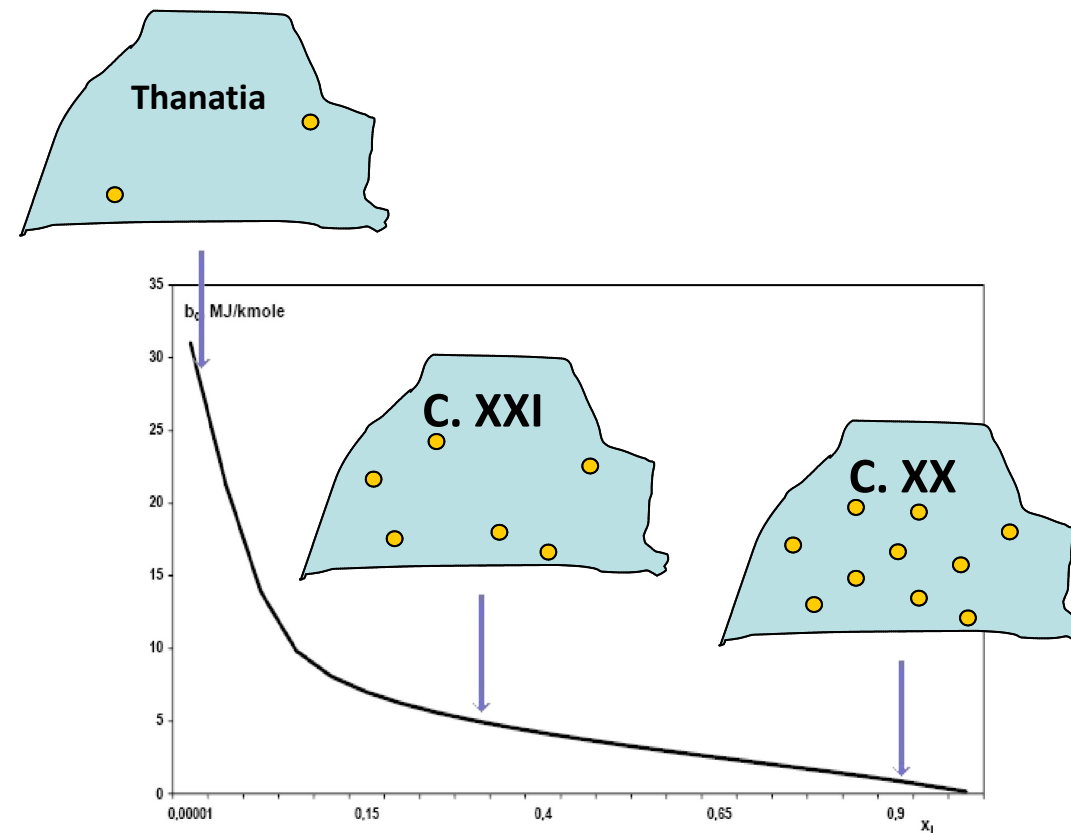
- 2) The lowest concentration state i.e. a degraded planet in which no concentrated materials exist.
 - Thanatia

Dispersion and Concentration Exergy

The minimum theoretical work needed to concentrate a substance from an ideal mixture of two components is given by the concentration exergy:

$$b_c = -RT_0 \left\{ \ln x_i + \frac{(1-x_i)}{x_i} \ln(1-x_i) \right\}$$

Dispersion is destruction!



Why Thanatia?

- First, all economically exploitable minerals and fossil fuels ever existed constitute less than 0.01-0.001% of the earth crust.
- Second, the complete combustion of Earth fossil fuels will only change the composition of current atmosphere in parts per million of CO₂ increase.
- Third, 97% of the hydrosphere is seawater, while only 3% is freshwater. Of this freshwater, just 0.33% is found in lakes, reservoirs and rivers, making it particularly vulnerable to pollution. Climate change further threatens freshwater reserves through the melting of glaciers and ice caps.
- **Considering these numbers one can say that abiotic resources are deeply scarce in the planet for the many generations and population ahead.**

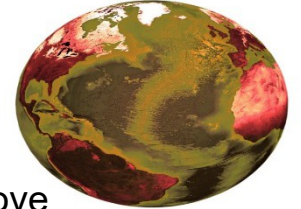


Source: Valero D., A.; Valero, A. & Gómez, J. B. The crepuscular planet. A model for the exhausted continental crust Energy, 2011, 36, 694 – 707;
Valero, A.; Agudelo, A. & Valero D., A. The Crepuscular Planet. Part I: A model for the exhausted atmosphere Proceedings of ECOS 2009, 2009

What Is Thanatia?

- **THANATIA ATMOSPHERE**

- An atmospheric injection of about 2,000 GtC.
- Carbon dioxide content of 683 ppm, a mean surface temperature of 17 °C (peak carbon dioxide induced warming of 3.7 °C above preindustrial temperatures),
- A pressure of 1.021 bar and a composition, on a volume basis of 78.8% N₂, 20.92% O₂, 0.93% Ar and 0.0015% of trace gases.



- **THANATIA HYDROSPHERE**

- freshwater is expected to increase its content of nitrogen, phosphorus, heavy metals, organic substances, sulphates and other components as population grows and climate changes.
- Most of Ice Caps melted
- The changes in freshwater composition should not affect significantly the composition of the ocean. Therefore, **the composition of the exhausted hydrosphere** can be **approximated** with high confidence to that of **seawater**.

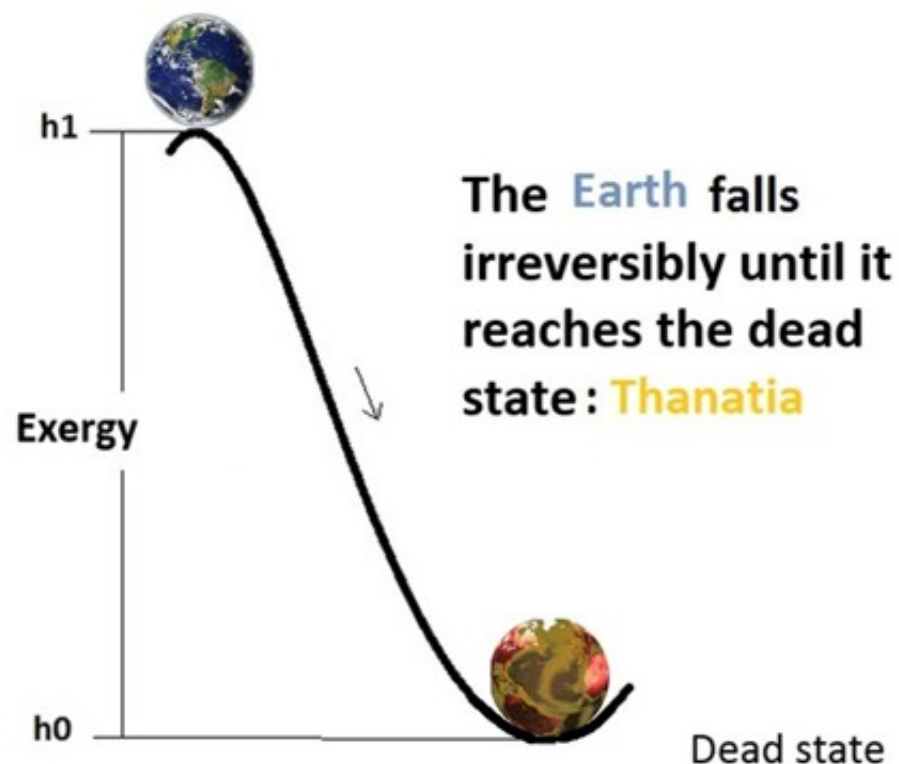
- **THANATIA CRUST**

- The upper continental crust can be approximated to **the average mineralogical composition of the current earth's crust**. The resulting crust is composed of 292 common minerals
 - All Mineral Resources have been extracted and dispersed
 - All fossil fuels on Earth have been burned

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The Earth as a Non-Equilibrium System

Why not considering Earth as a non-equilibrium system sunbathed by Sun with Humankind destroying Natural Resources to some End?



Mine to Commodity process



Chalcopyrite
x = mine ore grade Cu (0.6%)

**Exergy
Cost kWh**



Pure copper
x = 100% Cu

Thanatia to Mine process



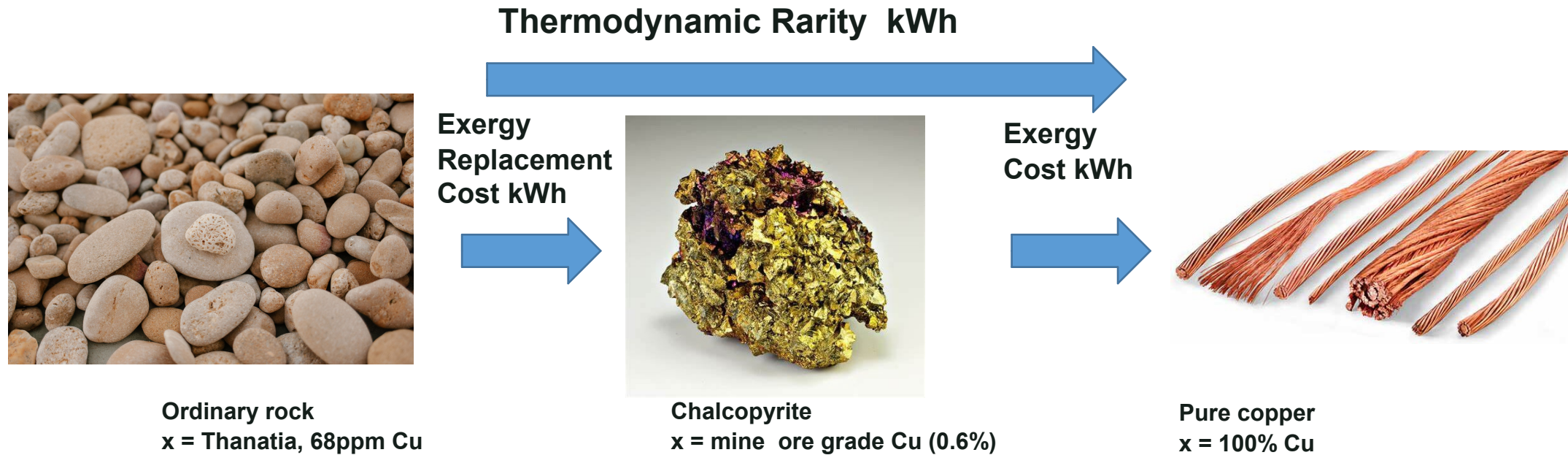
Ordinary rock
x = Thanatia, 68ppm Cu

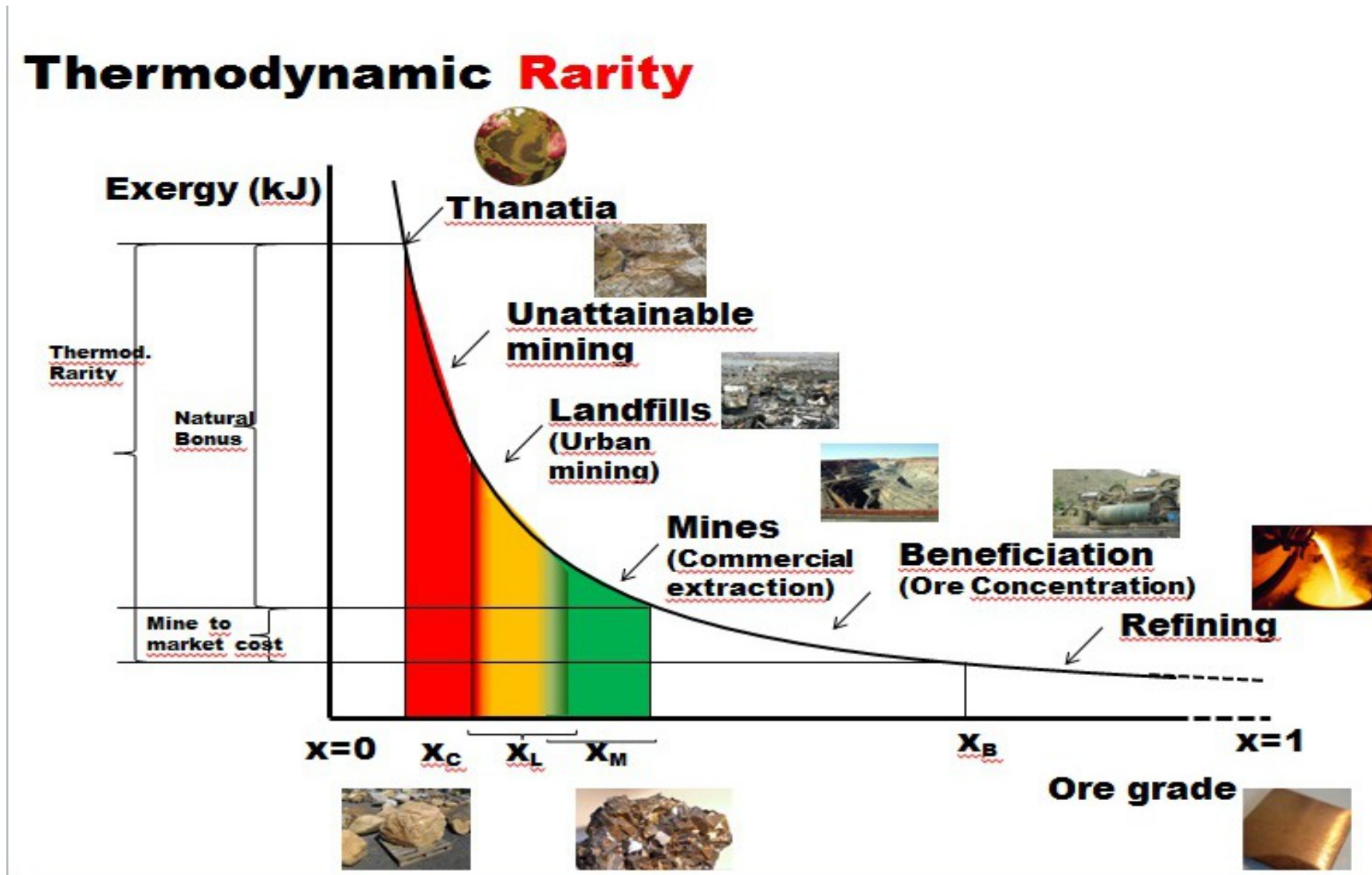
Avoided
Exergy
Cost kWh



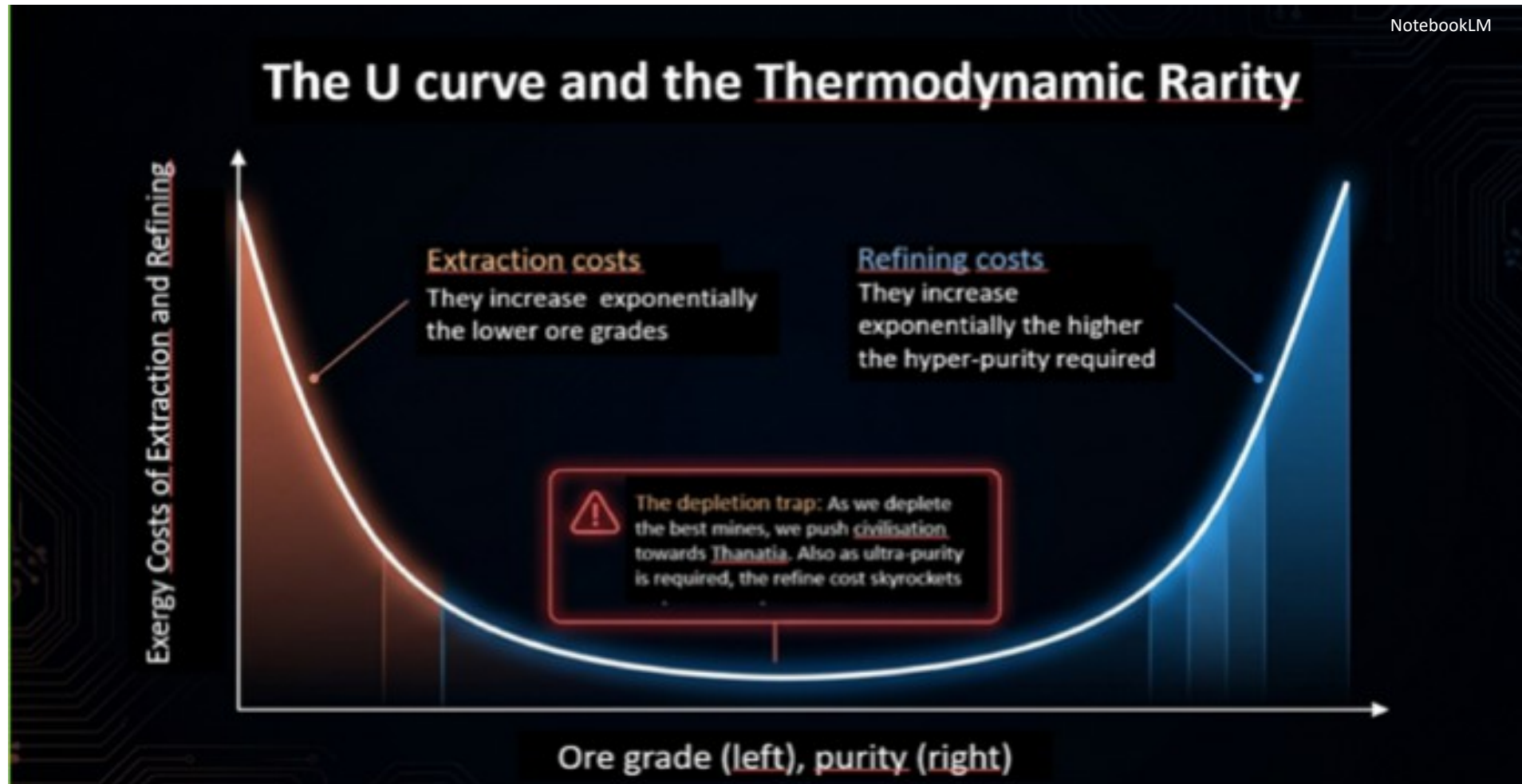
Chalcopyrite
x = mine ore grade Cu (0.6%)

Thanatia to Commodity





NotebookLM



The Concept of Thermodynamic Rarity

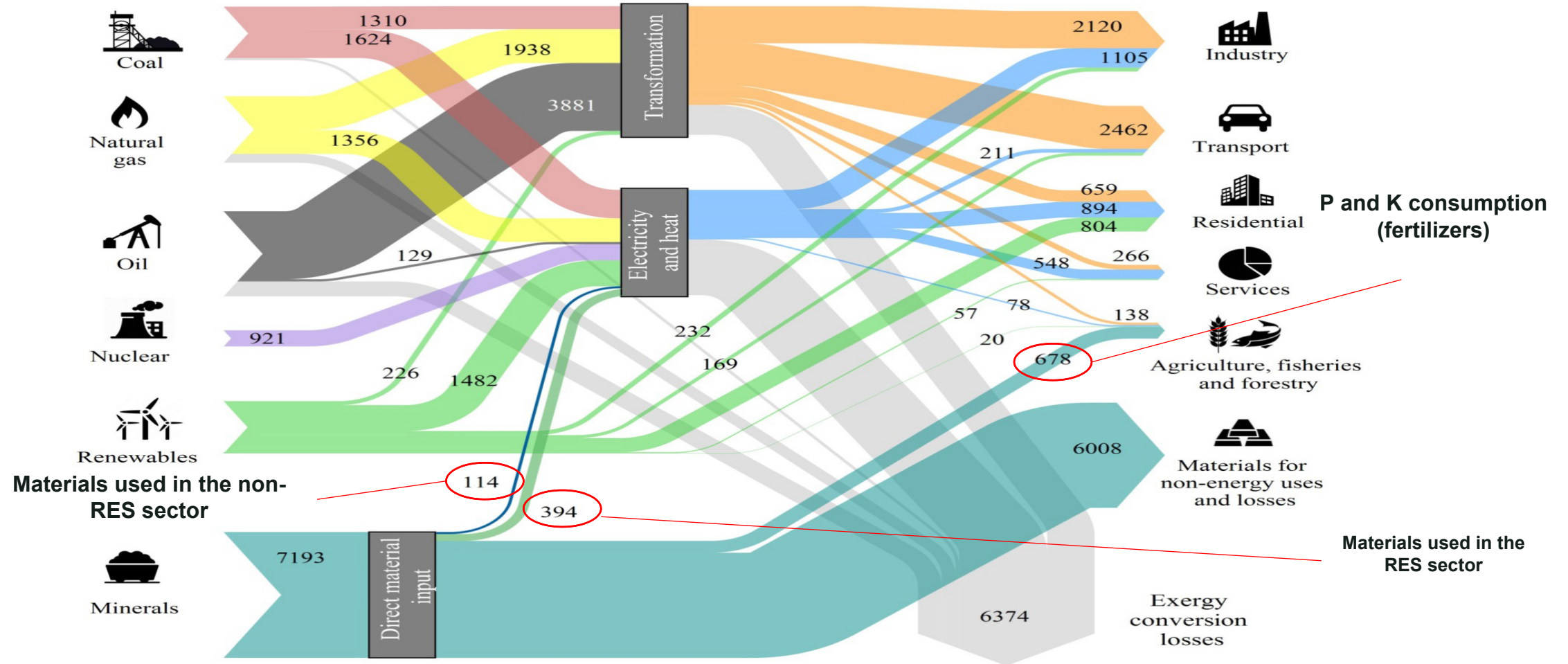
- It depends on the concentration of the mineral in the crust, the available technology to extract it , and the refining of the commodity in the market
- Like Exergy, it is a property of materials that can be measured in kWh.
- It is additive. The rarity of a mixed material is the weighted average of its component rarities.
- The lower its geological scarcity of an element (Thanatia), the higher its rarity.
- **Rarity means physical value. It is the main aim of recycling**

Thermodynamic Rarity of Selected Elements

H																	He
Li 558	Be 260											B	C	N	O	F	Ne
Na 47	Mg											Al 638	Si 1	P 1	S	Cl	Ar
K 1,227	Ca 3	Sc	Ti 23	V 1,191	Cr 5	Mn 16	Fe 18	Co 10881	Ni 776	Cu 139	Zn 26	Ga 754,828	Ge 24,247	As 409	Se	Br	Kr
Rb	Sr	Y 1,357	Zr 1,393	Nb	Mo 1,043	Tc	Ru	Rh	Pd	Ag 8,652	Cd 6,162	In 363,917	Sn 442	Sb 445	Te 2,825,065	I	Xe
Cs	Ba 39	La 336	Hf	Ta 485,910	W 7,642	Re 103,087	Os	Ir	Pt	Au 691,420	Hg 28,455	Tl	Pb 37	Bi 493	Po	At	Rn
Fr	Ra	Ac	Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub	Uut	Uuq	Uup	Uuh	Uus	Uuo
		Ce 620	Pr 873	Nd 670	Pm	Sm	Eu	Gd 4,085	Tb	Dy	Ho	Er	Tm	Yb	Lu		
		Th	Pa	U 1,090	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr		

	>10,000 GJ/t
	10,000-1,000 GJ/t
	1,000-100 GJ/t
	<100 GJ/t

Exergy Flows in the Energy Transition



*All data in Mtoe

[10.1016/j.energy.2018.06.149](https://doi.org/10.1016/j.energy.2018.06.149)

Pristinia: Assessing Fertile Soils

Exergy assessment of fertile soils and regeneration costs

A Growing Problem on a Limited Planet

Intensive Agriculture: production has tripled.

- ❖ **N** fertilizer consumption increased **10 times** from 1961 to 2013, **P** fertiliser consumption increases **4 times** in the same period.
- ❖ The amount of irrigated land has doubled.



80% of the increase in food production will be obtained with the **use of fertilisers** and **irrigation projects** (FAO predictions)

Loss of soil fertility

One third of the planet's land is severely degraded and fertile soil is being lost at a rate of 24,000 million tons per year.

Soil degradation is considered a threat to more than **40%** of the land surface¹.

The economic loss in **Europe** is estimate to be 1.200 million €/year, due to 12 million hectares of agricultural areas that suffer from severe erosion generating losses of **5 million tonnes of production**.

¹UNCCD, "Global land outlook report," 2017. Ministère de l'agriculture de l'agroalimentaire de et de la forêt, "Join the 4x1000 initiative."

Chaoqun Lu and Hanqin Tian. Earth Syst. Sci. Data, 9, 181–192, 2017

Panagos, P., Standardi, G., Borrelli, P., Lugato, E., Montanarella, L., & Bosello, F. (2018). *Land Degradation & Development*, 471–484.

Local Baselines



THANATIA

Physical depletion of a mine or the entire planet. Maximum degradation. Measure: The exergy cost of restoration/replacement



PRISTINIA

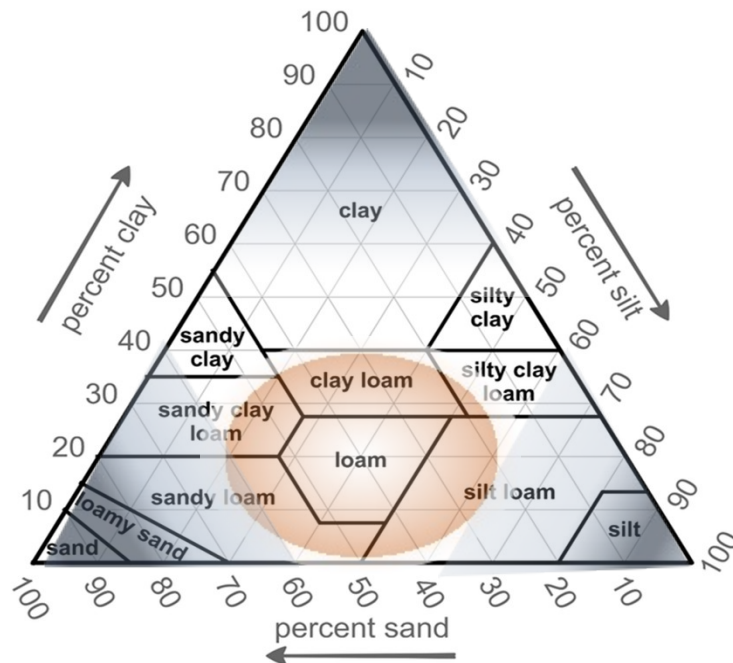
Maximum soil fertility (local), biodiversity and functionality. Measure: The exergy cost of regenerating a degraded ecosystem

Soils Are Complex Systems

Physical structure

Particles of different size (texture) determine water, oxygen availability, access of nutrients to plants and form the foundation of the plants.

Different types of soils with different properties



Biological aspects

Macro and microfauna are essential for the quality of a soil and influence nutrient cycles



Chemical composition

ORGANIC PART

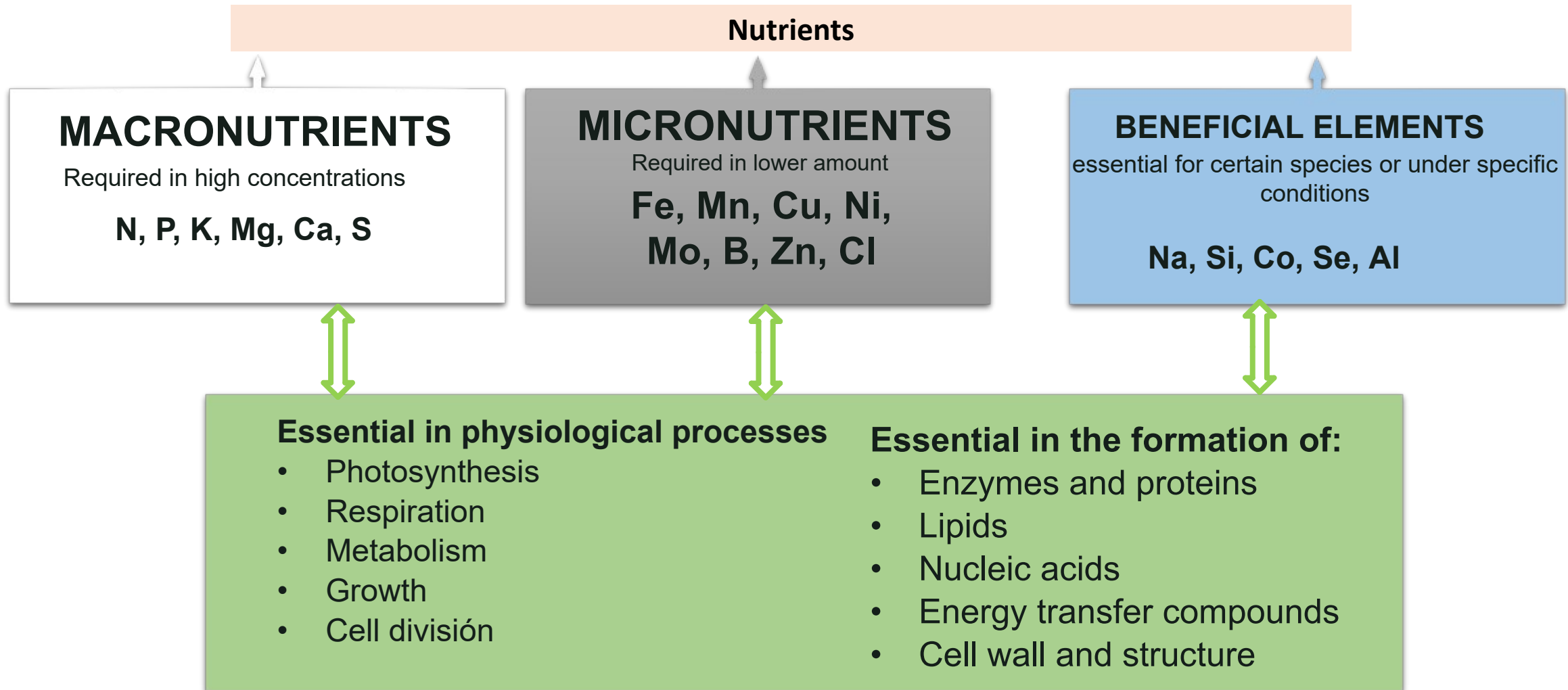
essential to improve the physical characteristics and as food for the soil biota

INORGANIC PART

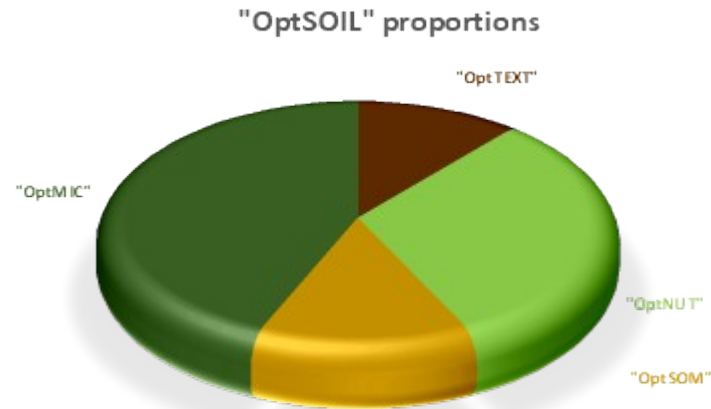
Plants need access to 19 nutrients from soil to grow



SCOPE: our first step to establish an exergy reference for top soil will be establishing the concentration and nutrients needed in a fertile soil



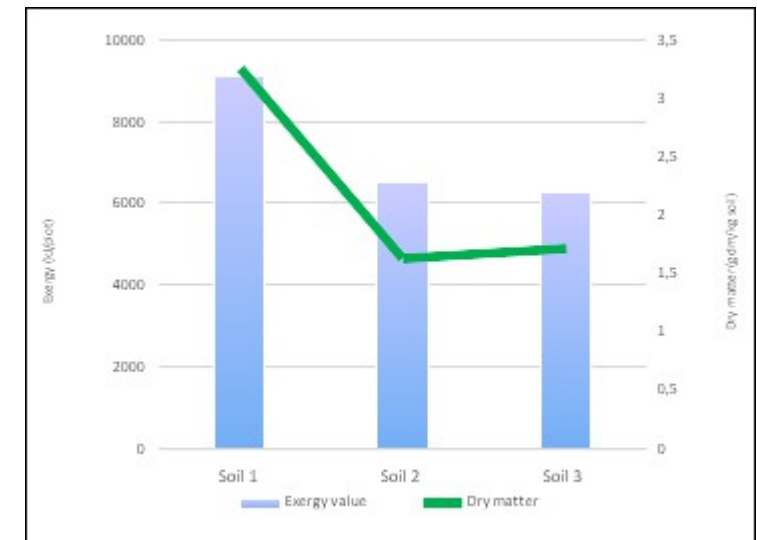
Soil System Study: The OptSOIL Concept



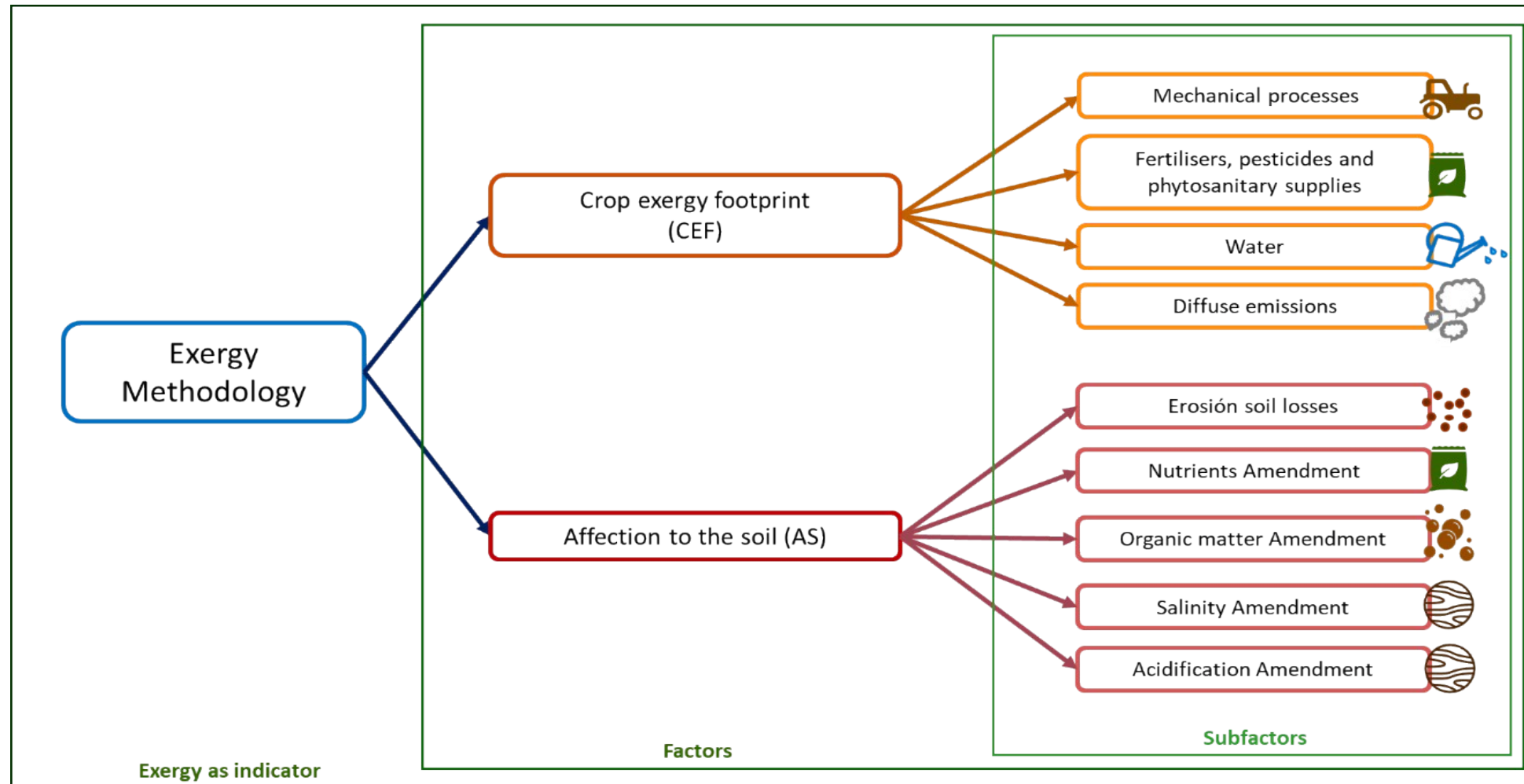
The independent study of the different components is useful to assess an exergy value to the soil, but fertile soils from an agronomical point of view cannot be understood interpreting each part independently but as a whole.

The developed exergy methodology was validated through the sampling of three soils in a greenhouse pilot test.

The results confirm that the methodology to calculate the exergy value of fertile soils is consistent with agronomic performances. That said, much more data would be needed to establish a relation between the exergy of soil and its yield, including the use of different crops.



[10.1016/j.ecolmodel.2021.109802](https://doi.org/10.1016/j.ecolmodel.2021.109802)



<https://www.cencenelec.eu/news-events/news/2022/workshop/2022-03-01-methodology-to-quantify-the-global-agricultural-crop-footprint-including-soil-affection/>

Summary: Pristinia and Thanatia

Exergy can be a useful tool to assess the complex problem of evaluating soil fertility or quality.

"OptSOIL" has been proposed as a fertile soil, and is based on the parameters:
microorganisms, nutrients, organic matter and texture.

An ideal fertile crust composed of "OptNUT", "OptSOM" and "OptMIC" invariant and independent of different local textures has been introduced.

The imaginary crust - bountiful fertile- has been established as PRISTINIA as opposed to Thanatia - sterile land - a dead state referring to abiotic resources.



Any real agricultural soil will be an intermediate soil between Pristinia and Thantia.

CEN Workshop Agreement on 'Methodology to quantify the global agricultural crop footprint including soil affection'



This European CWA specifies a methodology for identifying, characterizing, and implementing a single indicator to assess the quality and degradation of agricultural soils and the overall impact of the agriculture processes. The agriculture impacts are assessed through the mechanical, fertilization and irrigation activities associated. Furthermore, soil impacts is evaluated accounting with soil erosion and parameters such as nutrients, texture, and organic matter. The developed methodology allows a simple but robust assessment of soil biogeochemical processes and the loss of fertility and degradation teniendo en cuenta que hemos recibido varios comentarios sobre el tema de la biodiversidad y los soil animals, quizás sería interesante indicar en el scope, que se excluyen.

A **CEN Workshop Agreement** (commonly abbreviated CWA) is a reference document from the [European Committee for Standardization](#) (CEN). It is, by definition, not an official standard from the member organizations <https://www.cen.eu/news-events/news/2022/workshop/2022-03-01-methodology-to-quantify-the-global-agricultural-crop-footprint-including-soil-affection/>

Final Reflections

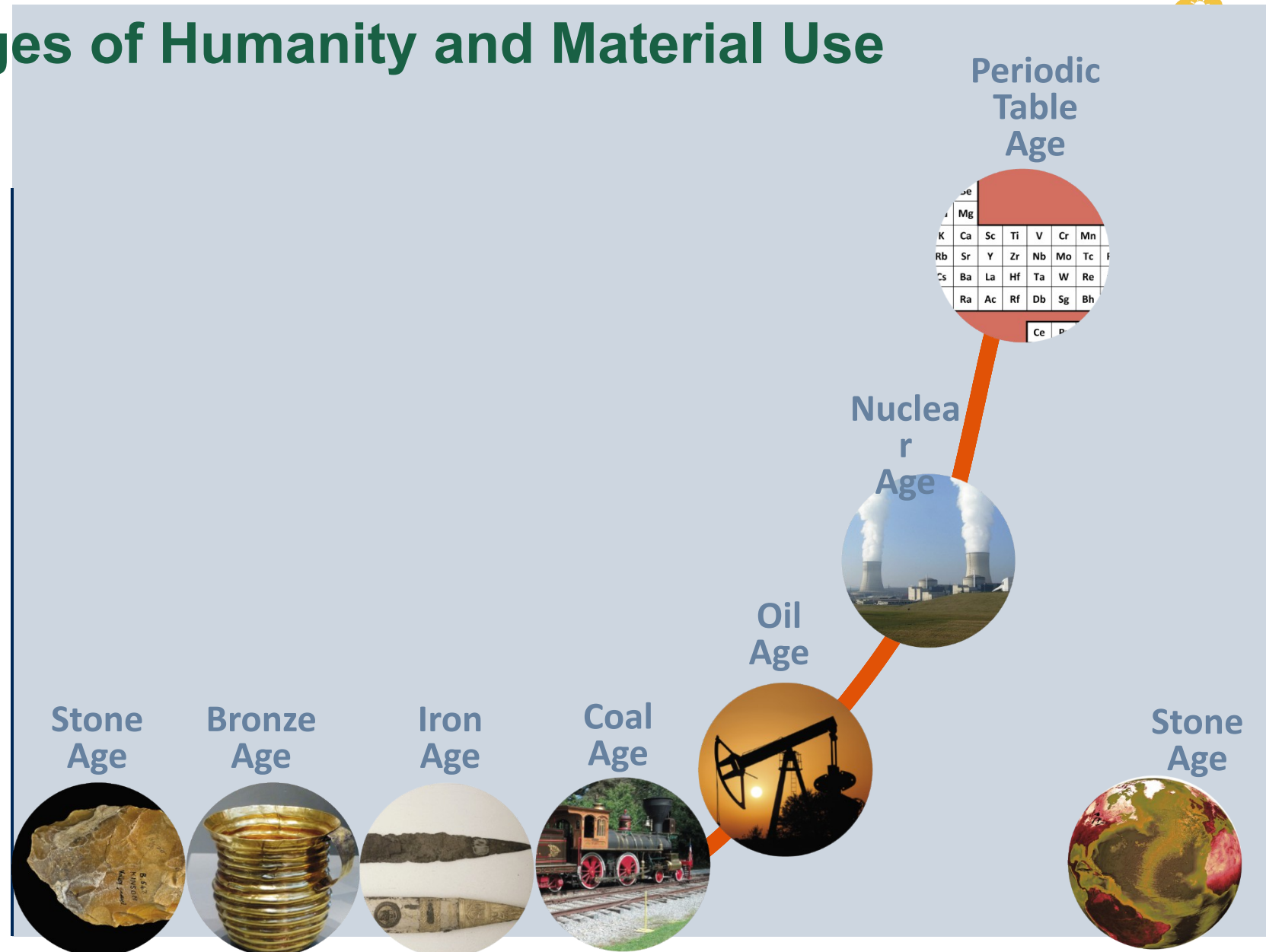
Accounting for Planetary Mineral Capital



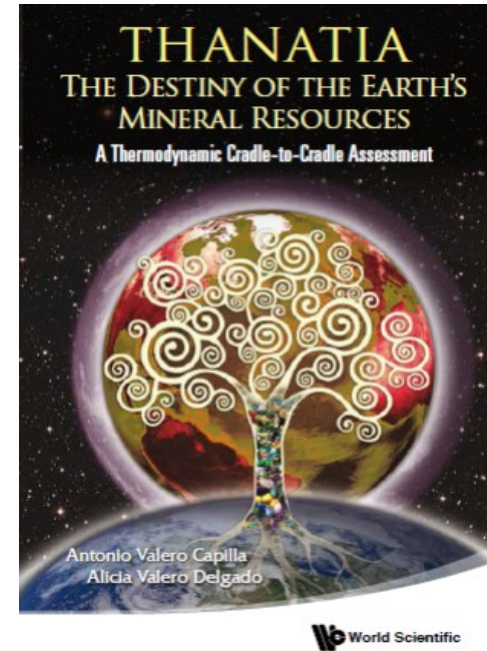
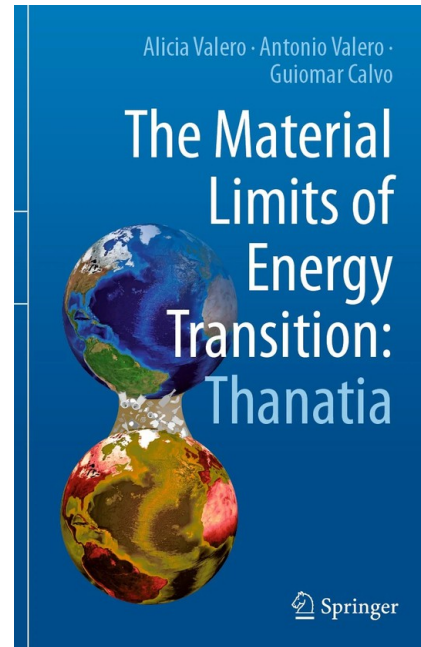
- Each year is one more year or one year less? What is Progress?
- Who dares to carry out an annual assessment of the world's loss of thermodynamic rarity?
- By postulating Thanatia we can quantify a thermodynamic limit of the Earth, and thus assess its Mineral Capital and its degradation velocity

The Ages of Humanity and Material Use

Rare
Material
intensity



Efficiency and Sufficiency



We need Efficiency and Sufficiency

Both can be improved understanding Thermodynamics!

Thank You

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