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RESEARCH ARTICLE

The Hectare-Year Approach: A Unified Space-Time Framework for Quantifying Biological and Geological Resource Regeneration

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Abstract: Sustainable resource management requires a unified, objective indicator to compare material and energy potentials to stay within the limited boundaries of our planet, Earth. This conceptual paper introduces the ha-year (hectare-year) unit of measure. It is the determining factor in keeping the Earth system within regenerative limits. With available space-time, it is possible to quantify annual reconstitution rates of all energy and material resources, organic and inorganic, ensuring their use remains within planetary regenerative limits. The dichotomy of "renewable" vs. "non-renewable" is challenged we argue that all materials cycle via biological, hybrid, or geological routes, powered by solar or geothermal energy.

By expressing resource flows in land-time relationships (ha-years), we establish a universal accounting framework for sustainable yields, rooted in the first principles of energy-mass balances. Illustrative examples (e.g., copper and aluminium) demonstrate the application of the framework, revealing the extremely limited geological regrowth rates (e.g., 0.0017 g Cu/ha-year). These data provide a foundation under evaluation methods, for instance to compare the resource demands required for food, infrastructure, against the finite land capacity of the Earth (~2 ha/person/year), thus exposing unsustainable claims and guiding land-use policies toward existential security.

Unlike traditional metrics (e.g., CO_2 emissions, which only measure end-of-pipe effects), ha-year data makes it possible to determine the root effects of resource depletion and land competition. The approach clarifies planetary boundaries from the physical supply-side perspective. It offers fundamental data catering for sustainable governance policies rooted in the first principles of an energy-mass balance. It keeps resources cycles closed, based on the capability of incoming solar energy and land to reconstitute resources. It replaces the failing “primary energy” approach, with an overall “primary land” approach.

Keywords – Ha-year, land-use, exergy, resource cycles, planetary boundaries, sustainable yield, exergy, geo-cycle, spacetime.

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1. INTRODUCTION

The initial background of this research is the quest for a single, unambiguous indicator to characterize resource cycles on Earth. It allows the objective comparison of material and energy flows and determines the maximum amount that can circulate in a cycle without depleting it. The ultimate goal is to make it possible to calculate an optimal global balance between use and the restoration of resources. This is a fundamental condition for sustainable life on Earth to live within the maximum available potential of energy and material cycles. In such a scenario, harmful side effects would virtually disappear.

So far, there has only been limited research focused on the essential thermodynamic balance between degradation and restoration on Earth. Mudd shows that the metal content in ores is sharply declining; we are depleting our rich, concentrated ore deposits (Mudd, 2007; Mudd, 2009). This means increasing amounts of energy are required to extract the same amount of pure metal, entailing great exergy losses. (Harmsen 2013).

Other, more traditional approaches to evaluate our physical system, start with ecological economics, relying on monetary valuation (Constanza et all 2014) or, for instance, pure

energy-based metrics, like Odum, using emergy: Solar equivalent joules (sej) as the metric, quantifying the regenerative capacity of the system based on solar energy (Odum 1996), which is also what Daly proposes with throughput not exceeding regenerative capacity. [Daly, 1996]. This is seldom linked to the time and space required for such a process.

In this respect, more is known about organic materials—how they grow, their renewability, and cycle speeds. Non-organic materials, minerals and metals, are often assumed to be "non-renewable" and thus unable to cycle (i.e., to reconstitute or re-concentrate in a natural manner). This assumption is incorrect, and only scarcely addressed. (as will explained below)

Bardi dedicated a book to the consequences of extraction (Bardi,2010), concluding that "none of the minerals we have so liberally dispersed all over the world will re-form in time for humans to use again".

Yet, they *do* recover; they will reform into useful concentrations. Through volcanism - especially underwater - via mineral processes as well as tectonic movements, metals and minerals are re-concentrated. In other words, besides biological cycles, geological cycles also exist. These cycles are driven by residual energy from the Earth's core processes, albeit on very long timescales—longer than humans can oversee. This does not prevent us from calculating and assigning a rate to these processes, giving a per-year cycle speed (Rovers et al., 2017). This forms the basis for a theory, built up in several preceding papers [Rovers 2022].

In principle, it is a matter of energy input to re-concentrate raw materials to usable levels, either by (non-human-interfered) ecological processes: geological cycles for in-organic substances recreating new rich deposits, or through human intervention, investing energy to re-concentrate.

Some research has been done in this field, but until now, there have been few well-developed, fundamental, and objective methods for calculating and mapping the mass flows of these in-organic substances. Early work started by estimating how much energy went into concentrating the already available resource stocks within the Earth system. From there, concentration losses* due to using these resources can be calculated (Odum, 1973; Odum, 1996) It is a brilliant approach but incredibly complicated.

Valero and Valero also explored thermodynamic resource flows in terms of exergy (Valero et al., 2021). They started with the opposite outset to Odum: suppose no quality is available at all on Earth; suppose a desert (thermodynamic equilibrium); how much exergy would be required to reorganize and create current concentrations?

These approaches use thermodynamic principles: the cost of resource degradation or (re-)organisation (Odum 1996, Valero 2021), with a focus on energy quality. (but not yet integrating sourcing energy from the planet's surface, ie within planetary boundaries).

More recently, Klinglmair and Kleijn, among others, investigated the quantification of resource flows in life cycle assessments (LCAs) (Klinglmair et al., 2014) (Kleijn, 2012), However the problem with life cycle approaches is that these contain different categories of side-effects (not causes), which are then subjectively weighed. Until so far LCA is regarded as the best method for the inclusive evaluation of impacts. However, it does not relate to the potentials of the energy and materials base, but instead is related to the impacts.

These methods are truly valuable regarding the impact and/or energy demand explorations, but are not directly related to the total capacity of the system to invest solar energy, for natural or human induced organisation of organic and in-organic geological sources. The ha-year approach introduces land as the foundational measure for these thermodynamic processes, since land is the intermediary between solar energy from outside our system to useful thermodynamic capacity within our system. It is also a limiting factor as well. Ha-year quantifies how much land is required to generate a resource and/or the land to collect capture and store the energy to produce or re-concentrate the resource, thus quantifying the yearly potential. It combines the limitations of exergy and space together. This holistic and practical analysis of human endeavor on Earth provides fundamental data supporting all kinds of assessments and evaluation methods. In previous publications, the ha-year approach was introduced for organic resources, and there was a first attempt to explore if metals could be integrated in the approach (Rovers 2022).

The ha-year concept also intersects with land-use theory, particularly the work of Vitousek et al. (1986) on Human Appropriation of Net Primary Productivity (HANPP). HANPP measures the fraction of terrestrial photosynthesis utilized by humans, but leaves out non-biological resources (e.g., metals). The ha-year framework extends this logic to geological processes, treating the Earth's crust as a 'slow' form of land use. Just as HANPP can reveal the biological limits of human activity, ha-year reveals the geological limits—a critical addition to a unified theory of land use potential. This also applies to another popular approach, that of ecological foot printing. Which is a plentiful resource of useful data for the ha-year approach. Originally however it only deals indirectly with land, the required land to theoretically compensate Carbon emissions.

The ha-year approach also complements the planetary boundaries approach (Rockstrom et all 2009) since it shifts the focus from end-of-pipe effects (climate change, biodiversity loss) to resource limits; resource use beyond regenerative capacity and the amount of land required to regenerate consumed resources. Planetary boundaries define the safe operating space, but do not show the implications

*loss of exergy, the potential to deliver work, to change environments, to provide quality

directly and the consumed potential of resource use. The ha-year land theory provides a simple, direct relation for the supply-side approach. This somehow relates to the work of Meadows as well, whose Limits to Growth relates things to physical land availability, though it does not yet include geological resource flows.

2. Regrowth routes & data

Here we can conclude that all raw materials, therefore, can cycle through a process of growing or restoring stock. The two main determining processes:
1. The biological route (the short, cyclical route).
2. The geological route (the very long, cyclical route), which is autonomous and driven by geological processes (volcanism, tectonics, geothermal energy), with cycle times of sometimes millions of years.

There is also a hybrid variant, where both geology and biology play a role. In the case of biological processes (ecosystem growth powered by the sun), sometimes aided by human intervention like farming, cycle times range from 1 to several hundred years.

For all variants of resource use, it can be said that to use them, they usually require additional energy investment to make them useful: extraction, transport, processing, etc. This part is the embodied energy, often labor and/or external energy. To be sustainable and avoid depleting the Earth system from the inside, an external source is required. The sun supplies exergy potential to the Earth system. This energy is ultimately captured via land, directly or indirectly, as a flux per m², i.e., land over time.

Geological processes can also be accelerated by human intervention, but only by investing enormous amounts of extra energy. If this energy comes from within the system, the net result is degradation. The (extra) energy must therefore come from the only available external source: solar energy, directly or indirectly (via food/labour or other conversions). An example: You can put a lot of energy into crushing rocks to produce sand, or wait for the sun and rain to erode mountains and gather the sand from rivers.

It is always an energy-mass relationship: The amount of material on Earth does not increase or decrease; it is a matter of concentration and organisation. The more diluted or dispersed, the more energy through natural processes or human stimulation is needed to return it to higher quality levels or a useful levels of organization. This is also the essence of evolution, both biological and geological. It's a balancing process between energy and material. More precisely: *e(nergy)* and *m(ass)* are condemned to each other, linked and in principle interchangeable, including process losses. They are not only linked in chemical processes at the atomic level, as we already know from Einstein ($E=mc^2$), but also in everyday mass/energy calculations. We on Earth are the lucky ones to receive (just enough) solar energy from outside our otherwise closed system to enable some growth, re-concentration, compensating thermodynamic degradation[†].

The measure: Land (use over time) as a Universal Unit
Why Land? First of all, the only source adding potential exergy (energy that can provide work) to the planets ecosystems is radiation from the sun. It's the basis on which existing systems have to survive, and growth of ecosystems and evolution can take place. It drives organization and concentration of valuable resources, storing and restoring capacity to change processes. This is what distinguishes the Earth form all other planets in the universe (at least until a similar planet will be discovered)

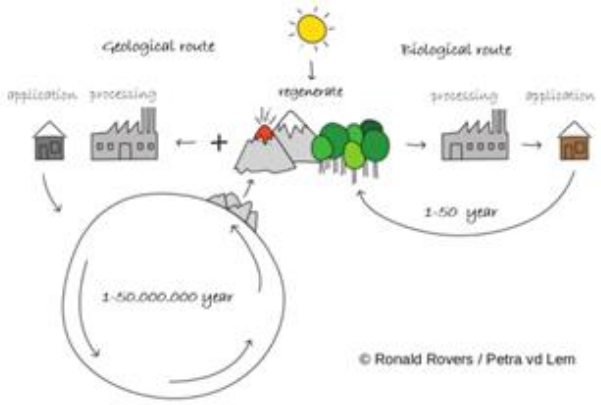


Figure 1. In some way all resources regrow or reconcentrate, creating a closed loop. However the time for such process can differ extremely. Short for organic or biological resources, (right) and very long for geological resources re-concentration routes, like metals. (left)

Land is the primary medium and measure to capture energy coming from the sun in flux per m2. As it always has been, fossil energy is the result of previously grown biomass at given densities per land area[‡]. The yield of many hectares of land each year or millions of years, in ha-year. Not only fossil energy, but also the wind and water cycle is driven by solar flux, as well as for food and most materials. In some cases supported by the remaining autonomous geological forces of the earth cooling-down process. Not only nature but mankind is completely dependent on what the earth surface can provide, from within a certain space above or below that land. A second link to land is the spatial constraint: the earth's surface is limited. The space needed to live and harvest resources has to be shared by all people and nature. Thirdly: comparability. Expressing everything in ha-year relates directly to the systems maximum capacity and allows a direct comparison between all resources. This makes it possible to calculate available potential. (for instance, to determine equal per capita shares).

The key measure is the potential that can circulate and cycle continuously. To do this, we must calculate how much is

[†]that is, we don't know yet if there are more lucky or even unlucky ones…

[‡]land with air or water above

annually re-concentrated via the short and long cyclical processes. Before moving on to calculations, some more detail about the ha-year unit of measure and the space-time relationship

For short-cyclical, mostly organic materials, this is straightforward: it grows in forests, on land or oceans (which is just land with water above) , in certain mass concentrations or yields per hectare per year (autonomous or with human intervention). This varies by species, crop, and location but is a common and logical way to determine annual availability and average productivity, based on solar energy input.

Trees grow in about 50 years, but can be averaged to calculate annual growth. The same applies to grain, straw, and many other resources. Land is needed; it is the intermediary between the growth of the resource and capturing the solar energy coming *from outside* the system. For centuries, it was the determining factor, until the use of fossil energy led to a huge extra energy potential enabling growth far beyond actual regenerative capacity, thus degrading quality within the system (and changing the system). The challenge now is to live within regenerative capacity, to do so it is necessary to make this capacity visible and calculable.

It makes sense to use the land-sun relationship for organic substances. But this relationship is also applicable to in-organic cycles. After all the energy required for extraction and processing—embodied energy—is also land-dependent, because ultimately nearly all comes from thes sun. This can be directly or indirectly converted into a (converted) flux per m², thus the required land over time, to capture and convert.
Next, the concentration process of some geological routes is also directly surface-dependent, for instance for clay, sand, and gravel: these are erosion materials that become available within a river basin, the capacity is dependent on total basin and mountain range area supplying the basin. As such they give the total flux potential over that land area, in a hybrid process (geological mountain forming, biologically induced erosion.[§]
Similarly, tectonic or volcanic deposits of metals have a global maximum (as will be described below) the total can be translated into land: how much becomes available per unit area over time. After all, it is also a certain flux from the Earth's interior to the (near) surface, distributed through weak spots. This creates a mineable quantity, averaged per unit Earth area creating useful data regardless of political boundaries.
In some cases, metals are even directly dependent on land area: manganese nodules on the ocean floor, in which metals accumulate over millions of years, growing in a certain density per hectare of ocean floor.

It therefore makes sense to use land as a universal unit of measure, in relation to time, so that everything, organic or in-organic becomes comparable. This is the central premise precisely what is central of this research. This research has been conducted for about 15 years named Maxergy ('maximizing exergy', www.maxergy.org). We are all living on the surface of the planet, not below or above, and are dependent on what the system can deliver as a continuously harvestable resources from the land.

The three types of routes, biological route, the hybrid route and the geological route, are in principle autonomous processes. Nevertheless, humans can intervene in each of these cycles, accelerating processes, however at a cost to other raw materials and energy from within the system. Or better, by using solar energy, which then requires land to capture and store that solar energy for use. Or, of course, with labor, which is again land-bound via food energy. Let's have a look at the routes and their land relation exploring some of the actual data.

The data is given in kg per ha-year, separated in local and global data:
local (l): *Data represents the yield in a specific extraction area (there may be multiple extraction areas), or a planted hectare (thus dependent on how many hectares are in use). To become global data averages, it is required to document all extraction areas, or know how much hectare is in use for a specific crop.*
global (g): *Data represents calculations for the current existing known source areas distributed and averaged over the total land surface (like forest area), or a geological process outcome averaged over the Earth's surface. (though not all geological contributions may be known yet).*

Biological route
In earlier research, an initial attempt was made to tabulate this approach through exploratory calculations. For the biological route—the short-cycle renewable resources—plenty of data is available from agriculture research. The collected data so far is listed in table 1

Table 1. Regrowth Speed in Space-Time (ha-year) for Organic Resources Following the Biological Route
Productivity and space-time requirements for organic resources through biological regeneration processes. Indicative averages.

Material	Productivity	Inverse	locality	Location
Oil* (fossil)	0,00027 **g**/ha-year	3.700 ha-year/**g**	g	Global
Wool	25 kg/ha-year	400 m²-year/kg	l	Per local sheep area
Cork	150 kg/ha-year	66 m²-year/kg	l	Per planted area, Portugal

[§]This is also the way to measure fresh water availability per land area, the flow of which is solar induced as well

Cotton	250 kg/ha-year	40 m²-year/kg	l	Per planted area
Shells	300 kg/ha-year	33 m²-year/kg	l	NL Wadden area
Oil-rapeseed	1.400 kg/ha-year	7,1 m²-year/kg	l	Per planted area, NL
Flax	2.000 kg/ha-year	5 m²-year/kg	l	Per planted area, NL
Straw	4.000 kg/ha-year	2,5 m²-year/kg	l	Per planted area, NL
Rapeseed	4.500 kg/ha-year	2,2 m²-year/kg	l	Per planted area, NL
Wood	~5.000 kg/ha-year	2 m²-year/kg	l	Per local hectare
Reed / Riet	6.500 kg/ha-year	1,5 m²-year/kg	l	Per planted area
Hemp	10.000 kg/ha-year	1 m²-year/kg	l	Per planted area, NL
Miscanthus	15.000 kg/ha-year	0,66 m²-year/kg	l	Per planted area, NL
Bamboo	20.000 kg/ha-year	0,5 m²-year/kg	l	Subtropics
Vegetables (open land)	30.000 kg/ha-year	0,33 m²-year/kg	l	Per planted area, NL
Seaweed	35.000 kg/ha-year	0,28 m²-year/kg	l	NL coast area
Potato	40.000 kg/ha-year	0,25 m²-year/kg	l	NL bio/labor farmers

Input data: Various sources, as specified on www.maxergy.org *-input data*
Notes: Productivity values represent the rate at which resources can be regenerated. Inverse values indicate the space-time requirement (area × time) needed to produce one unit of mass.
Locality codes (l = local, g = global) indicate the scope of the measurement as defined above.

Hybrid route
A calculation has also been made for continuous flow resources such as clay: clay is an example of a hybrid process, with a geological component (the uplift of mountain ranges through tectonic movement) and a biophysical component (the erosion of rock by sun-initiated wind and water forces) (Rovers, 2025). (table 2)

Table 2. Regrowth Speed in Space-Time (ha-year) for Resources Following a Hybrid Route of Regeneration
Space-time productivity hybrids for materials with mixed regeneration pathways.

Material	Productivity	Inverse	Locality	Location
Lime	30 kg/ha-year	330 m2-year.kg	l	S- Limburg region NL
Loam	1040 kg/ha-year	9,6 m2-year/kg	g	Global land area
Gypsum	13.300 kg/ha-year	0,7 m²-year/kg	l	Per brine area
Salt	5 **t**/ha-year (up to 600)	~2 m²-year/kg	l	Per traditional brine area

Data: *Various sources, as specified on www.maxergy.org -input data*

Geological route
For the geological route, the long cycle process, we have some initial calculations available; a starting test example is for iron (Rovers, 2022). Its estimated at 0,7 kg/ha-year (g) .
To further test the hypothesis that resources can be objectively compared and related to a max potential of the earth system, two more metals have been calculated acting as additional examples for the geological route.
The first example concerns Copper. a critical metal with well documented geological formation processes. The calculation in appendix 1 is not exhaustive but shows a geological generation rate of 0,0017 kilograms per ha-year (l), showing it is renewable, although on an extremely slow time basis. Based on this calculation a global estimate per ha -year can be derived, as a rough estimate, but incomplete. (other routes should be added). The local outcome is illustrative, additional routes are also expected to give extremely low global values.
A second example is given by aluminium. Illustrating a hybrid process, geological as well as biological (due to tropical weathering). Aluminium regenerates, via bauxites, at a rate of 1,75 kg/ha-year. This is an expected global average.
Both additional examples show like iron, that metals also go through closed cycles, and can be regarded as renewable resources, although many orders of magnitude slower than resources via the biological route. The strength of ha-year framework presently lies not in its precision, but in its conceptual clarity, it makes it possible to evaluate all resource cycles on an equal basis, and accordingly the availability for use.

Application: demand estimates
Once resource data is available it is possible to calculate the annually available portion of resources that can be utilised by humans, without depleting concentrated stocks. When use, demand or application stays within these limits, the situation on earth is sustainable and maintainable. Creating a stable natural environment.

Table 3. Regrowth Speed in Space-Time (ha-year) for Metals Following the Geological Route
Productivity and space-time requirements for selected metals based on geological regeneration processes.

Metal	Productivity	Inverse	Locality	Location/Nos
Copper	0,0017 kg/ha-year	588 ha-year/kg	l	CCZ area (~132.000 ha)
Platinum**	12,5 **g**/ha-year	80 ha-year/kg	l	Streets in UK (dust)
Iron	0,7 kg/ha-year	1,42 ha-year/kg	g	Global
Aluminium	1,75 kg/ha-year	0,57 ha-year/kg	g	Global

Various sources as specified on www.maxergy.org *-input data*

It is expected that this also results in virtually no pollution, or at most, pollution at a level that the Earth system can take care of in a balanced manner.

There are many ways in which this data can be used to support existing evaluations, assessments or policies. That is not the core of this paper. However, some explorations have been made to translate the data into space time requirements for general needs by people, in products or activities. Already giving some indication of a balanced availability of resources for people.

We have to realise that there are approximately 8 billion people on Earth. Dividing the planet's land surface by this number yields roughly 2 hectare-years per person per year available for living. This is the amount each person 'can claim' or use. Of course, not all 2 hectares are directly available to individuals—some is shared for cities, roads, and, importantly, must be reserved for nature and biodiversity to maintain a functioning system. However, in principle, the potential of these 2 hectares—what they can sustainably yield—is available per person (max supply). The actual land used for human activities or products is referred to as "Embodied Land", also measured in hectare-years. This represents the "demand side".

See the accompanying Table 4 for an overview of the current demand request.
The demand can also be expressed in ha-year, so that it is possible to relate supply and demand cycles.

Food is the most important factor: Third-party calculations show that a biological diet requires about 1,700 m² of land per person per year (in a Dutch climate), a vegetarian diet about 1,000 m², and a vegan diet about 600 m² (Terluin, I. 2013, TNO 2017 and others).

The short-cyclical biological cycle can also provide other resources, besides food, it can also supply building materials or clothing (think "vegetarian building" and "vegetarian clothing").

It should be noted that in the Netherlands, a densely populated country, only about 0.17 hectares (1,700 m²) per person is available within the country's borders. This leaves little room for other uses besides food. (in a closed-cycle approach)

Hybrid processes are mainly flow processes with a large, relatively unconstrained flows over time, such as clay used for building. It is no coincidence that about 2.8 billion people live in clay houses—a virtually endless resource available on a broad scale (World Housing Encyclopedia, accessed April 2026).

Resources dependent on geological processes are only available in extremely limited, sustainable quantities. This is certainly true for copper, and previous calculations have shown the same for iron, despite its abundance on Earth. If we take the formation process as our starting point—the concentrated deposits per unit of time—the Dutch share for iron would be just enough for, say, one bicycle per person per life (in NL) ††.

The table shows a selection of human demands and their land claim expressed in ha-year, the land to be reserved for supply. Per year or per lifetime (lt).

** *Regarding Platinum: normally it's part of geological processes; here I took a shortcut from data on dust sweeping in UK streets, to be regarded as a thermodynamical equilibrium area. Actual geological data have to be developed and could be higher. https://www.forbes.com/sites/timworstall/2013/07/15/the-streets-are-paved-with-gold-and-platinum/*

†† A bicycle weighs around 10 kg, suppose iron. Iron yield is 0,7 kg/ha-year, so it requires 14,2 ha-year iron production area. In the Netherlands people have only 0,17 ha available per capita requiring a budget of ~ 82 years for the bicycle. Or the lifelong budget of 1 person.

Table 4. Land Occupation in Space-Time (m²-year) for Products and Activities
Land requirements for various products and activities, excluding second and third order impacts.
Products

Product	Unit	Land requirement (m²-year)	Frequency
A chair (grown)	1	12	Once per action
Sweater-wool	1	500	Once per action
House	1 m²	800	Once per action
Grave (at cemetery)	1	3 /year	Permanent-lt
Laundry dryer	1 drying cycle	0,548	Once per action
Clothesline	1 drying cycle	0,175	Once per action
Affluent menu	1 person	2.000 /year	Permanent-lt
Biological menu in NL	1 person	1.700*** /year	Permanent-lt
Vegan menu	1 person	600 /year	Permanent-lt
Bicycle	1	100.000	Once per action

Activities

Activity	Unit	Land requirement (m²-year)	Frequency
Sports av.	1 h/day	21 /year	Permanent
Golf	1time /week	600 /year	Permanent
Horse riding	1 person-1 horse	10.000 /year	Permanent
Leisure	1 h/day	77 /year	Permanent
House-cat	1	3.000 /year	Permanent
Religion	-	3,6 /year	Permanent
Culture	-	pm	Permanent

Various sources © r.rovers-Ribuilt. Data on www.maxergy.org -output data (230226).
**** Biological menu in NL value may have specific notes in original source.*

3. DISCUSSION

What makes this approach relevant? The ha-year approach makes it possible to objectively compare resources of different kinds, and the long-term potential for humanity to stay within a closed cycle.

For years environmental analyses primarily focussed on impacts, the end of pipe effects of our energy and resource use, mainly measured in CO2. This only addresses the main threat to life on earth due to climate warming but it is one of the many effects of our life style. More importantly it distracts us from the real limitations in energy and material consumption beyond regeneration capacities. This is somewhat indirectly addressed in LCA approaches, but these lack real fundamental analyses of the workings of resource cycles.

The currently popular approach of circular economy seems to overcome this, at least the part that is meant to be ‘ circular’ part, however in practice this deals mainly with reuse and recycling, and many other R’s, which is in fact a linear decay of resources going through a cycle, not addressing full restoration of resource stocks, specifically not concerning in-organic resources, which are framed as non-renewable.

A few words more on this issue: . The geological process can be regarded as the natural re-concentration route of a resource, for mineral and metals. To speak of a closed cycle or circularity implies restoring the original stock, which in principle happens along this natural route, biological and/or geological, for organics and non-organics.

Other strategies, besides natural stock growing, can be recycling and recovery, to refill and reconcentrate previous depleted stocks. These strategies are human induced actions, which require a lot of additional energy, that is, require depleting another resource stock to speed up the original process. While in most cases it’s not even about closing a cycle, just prolonging the resources in use .

The relevance of this research, in defining a ha-year unit to define the cycle potential for all resources, provides a fundamental basis for a more holistic approach to our energy and material addiction, it uncovers the root cause of our environmental problems. Its not an assessment in itself, but gives objective and basic data to build upon to evaluate human activities.

These cyclic processes, based on the capture and conversion of solar energy as an outside input to the earth system, make the earth continuously habitable. The expression in ha-year closes a long standing gap between the energy and land use approaches, combining it into a unified metric.

This also overcomes the primary energy fallacy, where all energy is compared to a hypothetical energy potential of fossil fuels, neglecting the land required as the ultimate source for fossil fuels and the time to convert biomass. Primary energy incorporates many failures: it relates everything towards only one source (fossils) one changing the world climate, it neglects the process to create fossil fuels, (including the sun as the real primary source) and falsely claims much higher energy potential, while the available exergy is much lower. Thirdly it neglects the materials needed to create useful

output. By using the here proposed land approach, all these issues are overcome, its all related to the capture of incoming solar energy on land, the only and real primary energy source, required to convert and store it. In fact with space time, the primary overarching unit is land use.

This approach also offers a solution to the euphemistic and misplaced use of the expression non-renewable resources. After all, all resources are renewable.. I propose to refer to all resources as re-growable, the ha-year approach normalises the time scales on which these processes happen. The illustration below shows how the ha-year approach could support and improve resource evaluation methods and assessments. To clarify how ha-year complements and extends existing frameworks, we compare it to other key approaches in sustainability science.

Table 5: What Ha-Year can add to Sustainability Frameworks

Framework	Unit	Focus	Strengths	Limitations	What Ha-Year can add
Emergy	Solar equivalent joules (sej)	Energy quality and embodied energy	Captures thermodynamic costs of resource formation	No relation with spatial constraints (land area)	Adds land as a limiting factor for regeneration
Exergy	Joules (J)	Available energy (work potential)	Quantifies resource quality and degradation	Does not account for land or time	Provides spatial and temporal dimensions involved
Life Cycle Assessment (LCA)	kg CO_2-eq, etc.	Environmental impacts	Comprehensive impact assessment	Effect-focused, and volumetric not supply-side (not cause related)	Addresses root causes (resource depletion) upfront
Planetary Boundaries	N/A	Earth system stability	Holistic, science-based limits	Abstract, not actionable for materials	Provides actual physical supply and demand-side limits
HANPP	% of Net Primary Productivity	Land use for biomass	Quantifies human land appropriation	Limited to biological resources	Extends to geological resources
Ecological Footprint (EF)	Global hectares (gha)	Biocapacity and demand	Measures human demand vs. Earth's regenerative capacity (for 1 effect, CO2)	Focuses on biological productivity for CO2 balancing	Ha-year provides a physical, resource-specific complement: ha-year measures real land capacity in terms of regeneration rates for all resources (including metals and minerals).

However, the space-time approach so far still has some limitations.

1) Calculations are average regeneration rates, but can vary depending on location, biological circumstances in different countries, and geological processes can vary depending on climate as well, (bauxite formation is faster in tropics). In that respect: 1 ha-year is the same value everywhere, however the output can differ depending local conversion rates.

2) Human intervention. For clarity autonomous cycles are assumed, but human interventions on the earth surface can greatly influence yields. For instance, fossil fuels can still be forming in a million-year process; however, the current biological deposits get no time or space to settle and get processed by Earth movements, due to the fact that all land is currently in use. (except maybe submerged land), but also here the land is under threat.

3) The quality and kind of resources differ; their use therefore depends on choices made by mankind. Ultimately, the data should be used to choose the right material for a function, based on (re-)generation rates and availability without disturbing cycles.

4) Averaging globally. A major issue is averaging over global land surface. For trees in standing woods its obvious: divide the actual global tree areas over total land and the global potential of wood at a point in time is clear. For other resources the generation rates can be calculated locally, but distribution over all global land requires an estimate of the total generation potential for the specific resource. An example: its easy to estimate the potato yield per 1 hectare-year, but this is a local given figure (l) It depends how many hectares are planted with potatoes, what the global yield per hectare will be. Another example: for copper we have an estimate on the yield per hectare-year for one area where manganese nodules can be found. This can be averaged globally, but is in that case a relatively low estimate. There

are more and sometimes unknown areas with nodules, and not yet calculated routes to concentrate copper. Only if we know all available sources, can we say what the average reconstitution speed is globally per ha-year. While the data available now is known only for part of the process, or part of the locations. Nevertheless, they already provide a rough indication of the magnitudes.

This local/global diversity, however, does not influence the use for individual cases. In the case of copper: distributed evenly it can give a certain quantity available per year, and per country or per capita globally. Despite the remaining lack of some of the data, it is still possible to calculate how much ha-year is consumed (at least) by 1 person in a year, for instance. Or how much ha-year is involved in building a house: how much land is claimed for how long to compensate for the resource use, to restore resource stocks.

5) Yields can vary depending on location, due to climate, land fertility and geological activity. It requires more research to show full potentials within reasonably trustworthy bandwidths.
6 embodied energy, the energy to harvest process and distribute a specific resource is not part of this papers research. But should of course be included when the data is used for real life assessment and evaluation of activities. The embodied energy should of course also be expressed in ha-year units as well

5. CONCLUSIONS

All resources are renewable / re-growable, and all their potential can ultimately be expressed in terms of land use over time. Land is the primary medium for capturing and converting the only external input source (the sun). Land is the medium on which humans must rely for conversions. Thus, space time—land use over time— (or cycle speed) is the ultimate unit for expressing and managing resource flows. At the front end, it determines the formation rate and speed of resource concentration, so that humanity, at the back end can consume these concentrations and stay within the maximum available potential of the limited land surface area on our planet. The only additional resource is solar energy.

The advantage of land-time-use data is that it is source data; there is no need to control side effects or end-of-pipe processes such as CO_2, it directly reflects the load and potential. It also allows a direct relationship with actual land use, with living off the land, as the intermediary between Earth and external solar energy. This makes it possible to steer policy toward land-use planning reflecting availability and accounts for example for crisis situations, ensuring that basic provision remains within our own country borders or cooperative frameworks, giving a form of existential security.

It also clarifies which ('non-essential') activities place a disproportionately large claim on land for little gain. In this regard, the figures on sports and culture - things not directly essential for survival - provide good insight into how to manage this effectively.

A few final notes:

- Remember that many processes also require secondary and tertiary resource use, and thus extra land, which is not yet shown in this exploration. Like factories to be build, roads, etc. And on the application side, when evaluating buildings: roads and infrastructure for buildings are usually not inclusively considered (in surface as well as for required resources).
- Calculating in primary space-time relationships (land use) remains a general, rough physical analysis. Locally, numbers may vary, and assumptions can vary widely. Nevertheless, land-use numbers provide a good indication of the scale at which we have to calculate and steer to stay within sustainable long-term potentials.

This research makes clear all materials *do* have a cycle, and denying this can be seen as conscious misinformation leading to depletion and decline. The old classification, with the non-renewables class is a human construct, not a physical reality. Even the latest scientific approaches still ignore this today. That it takes millions of years to re-concentrate for some metals, does not mean that it should be ignored.

There *is* restoration or regrowth of concentrated stocks for minerals and metals, and we must account for this to avoid unnecessarily discriminating against organic substances, where restoration *is* taken into account. As such this approach can help demystify the concept of non-renewable, which is non -existent. All resources are cyclical, re-growable and should be treated as such. To summarise: all resources are equal. All resources are renewable, or even regrowable , along different pathways. This is a first attempt to quantify these processes, which need to be extended and validated.

It provides a unified way to asses organic and in-organics in the same way, directly involving a level playing field for the required land.

While energy is the driver of all process, land is the essential measure. Land determines the potential of the system to capture, store, re-concentrate material stocks as well as the energy required to further process the materials.

Most importantly, the ha-year approach provides an upfront way of estimating the damaging effects of the processes for society. Instead of an end of pipe approach afterwards, mopping while the tap is open.

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Further reading/More background
The brochure (in NL): https://bewustbodemgebruik.nl/wp-content/uploads/2021/08/Volhoudbaar-landgebruik-BROCHURE-2021-1.pdf

The previous published paper (UK)
https://iopscience.iop.org/article/10.1088/1755-1315/1078/1/012125

The book: a Space -Time economy – (embodied) land as the capital for post-fossil living, ebook available at: https://www.ribuilt.eu/winkel/ (Dutch version available as a paperback: Post Fossiel Leven, same website)
Methodology and updates via Tools and Data section of the dedicated website: www.maxergy.org

Further notes
* Polymetallic sulfide deposits (PMS) are metal-bearing mineral deposits that generally form over tens to thousands of years, primarily around spreading ridges at the boundaries of tectonic plates. At these locations, superheated fluids emerge from the seabed and mix with cool seawater, causing minerals to precipitate both above and below the seabed. PMS deposits contain high concentrations of the base metals zinc, copper, and lead.
** Cobalt-rich ferromanganese crusts (FMC or 'crusts') accumulate over millions of years on the flanks of seamounts and ridges in the open ocean, and processes similar to those of PMN play a role in their formation. Crusts can become up to 25 cm thick and cover tens to thousands of square kilometres of seabed.
*** It is also important to note that more than 50 percent of the seabed megafauna in the CCZ lives in nodule territory. (Bardi, U. 2010)

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