Circularity of building materials: A non-discriminating calculation methodology

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Abstract. The energy transition has shifted impacts to materials, their energy use and potential depletion. Especially affected is the building and construction sector, since it is the sector which has the largest consumption of materials. Therefore, it is of utmost importance that materials cycles be closed as well, that they stay within system boundaries, and that we use objective calculation and evaluation methods. If we look at organic or biobased resources, the basic impacts in their flow are obvious and can be characterised fairly simply: they grow on the basis of solar energy at a certain speed and volume per unit of land. It’s a constantly renewing flow, with use maximised to what naturally (re-)grows. In-depth analyses have created growing awareness that non-organic materials are also in fact renewable, even without human intervention but in different scales of time and volume, in time frames way beyond the normal planning horizons of humans. They are renewed by volcanic and tectonic movements of the Earth’s crust. The paper explores how non organic materials will renew, that is, become re-concentrated in the Earth’s crust. In fact it is the concentration that is crucial for effective use, without additional energy input that would deplete other sources. From this analysis it follows that all resources can be characterised by the speed and volume in which they concentrate—either by the soil and solar route, or by the Earth movement route. : “Resources can thus be grouped into four categories: regrowable, streaming, slow and synthetic. The characterisation shows a similar pattern in other indicators for these resources: the slower the resources are regenerated, the more (embodied) energy required to obtain the resources, for instance. This is an attempt, a pre-study, to set up a methodology, and the first estimations for the global flows of resources in different categories. In the end it turns out that all resources have a natural renewal basis, and that there are no sustainable or non-sustainable (or non-renewable) resources: it is their use, within maximised flows, that determines their sustainability. It requires that we redefine the notion of ‘circular’.

Keywords: resources, renewable, circular
1. **Introduction and arguments**

The building and construction sector is currently transforming the built environment by creating energy-neutral houses and neighbourhoods that run on renewable energy. Solving the climate problem this way, with a focus on CO2, involves lots of materials and equipment, and shifts the burden to exhaustion of material stocks. As we also need to shift to renewable energy, this requires that we have to stay within the natural speed of regeneration of resources; otherwise, we will deplete our (concentrated) material stocks. And that’s before we even consider the enormous cost in embodied energy to process and use those materials; already, up to 50% of the energy impact of a new building is related to materials [1].

That the materials situation is already causing problems is illustrated by the case of the most used resource after water: sand. In most parts of the world sand is scarce, and is already illegally traded [2]. Sand is mostly used for concrete, but concrete requires a rough grain of sand. Sand grains in most deserts are too round to use in concrete. As a result, sand is stolen from beaches overnight or illegally mined from sea beds, with soil movements and disappearing islands as a consequence. While sand grains are continuously being formed by wind and water erosion in mountain areas, the speed and volume of use is much higher than the natural replenishment. Nor is this depletion happening only to sand: the human race already moves more soil and rock than the Earth’s tectonic and volcanic systems do [3].

Similar processes are taking place with other materials. As Mudd already demonstrated, the ore grades in mining areas are dropping fast. We are running out of concentrated stocks [4,5], requiring ever more energy to extract the same kilogram of concentrated mass [6]. This is visible in skyrocketing prices for copper and other metals. Knowing that the number of constructed buildings worldwide is expected to double in the next decades, the building sector, as the largest consumer of materials, is responsible for large part this dilution and desertification of materials, which may ultimately lead to its collapse.

The main issue in this paper, therefore, is about treating material resources in such a way that we can enjoy their use, while securing their availability in the future. Such treatment requires the use of these resources in a way that *stocks can re-concentrate in volume and speed within the time-span of their use*. This leads to the research question: “What is the natural speed of resource flows (without human interference) through the Earth system, not only for materials of organic origin, but for minerals and metals?” This paper analyses the cycles of different types of resources (organic, mineral, metal) and estimates their ‘flow rate’, which determines how much we can annually extract without compromising the total system.

The general principle of resource cycles is thermodynamics. This teaches that everything degrades, energy and raw materials alike, within a closed system. That is, it becomes diluted and its usefulness is lost (exergy). And when it comes to raw materials, the Earth is a closed system. So despite having large stocks of materials available on Earth, their concentrated availability is degrading, regardless of whether that resource is stone, ores, or fossil fuels. Not to mention the devastating side effects of their use, such as pollution and climate change. In the long run, by the way we treat these resources, we will soon have nothing but dust to play with—unless we put a lot of energy into restoring them again. But if that energy also comes from inside the system, then we still degrade the system as a whole.

The only resource that doesn’t ‘run out’ is what comes from outside our planetary system: solar energy. Interestingly, some terrestrial substances do re-concentrate themselves under the influence of that solar energy. First of all are the organic substances in the form of wood in trees, along with fruits and vegetables in plants, for instance (and yes, even in the form of animals and humans). That is the part that society can sustainably use, that feeds each other and can do work. That, in turn, is exclusively associated with ‘land’ as the medium to absorb, capture and convert that solar energy [2].

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1 Concentrations of all metal stocks are decreasing. Copper in most mines has gone down to 0.5%, from a high of 2–4%. In some mines in the past 20% was common [4].

2 Land is to be seen as both a surface with air above it or as a surface under water.
Regarding non-organic resources, so far there are not many well-developed fundamental and objective methods to evaluate their flows of mass and materials. In the last century, Howard T. Odum used thermodynamics to calculate the exergy of resource flows. He started estimating how much energy went into concentrating resource stocks that were already available within the Earth system. From there he could calculate the exergy losses using these resources [7,8]. It was a brilliant approach but incredibly complicated. More recently Klingmair and Kleijn among others [9,10] investigated quantifying resource flows for use in LCA’s, and Bardi dedicated a book to the consequences of extraction [11]. Here he concluded that, regarding the volume of resource flows used, “None of the minerals that we have so liberally dispersed all over the world will re-form in time for humans to use again.”

However, they will at some point re-form or re-concentrate: “In tens or hundreds of millions of years, a large fraction of what we have dug from the Earth will have been transported by the oceanic conveyor belt to the edges of the continents and recycled in the mantle. Part of it will have returned to the surface in the form of ores and deposits.”

The ‘maxergy approach’ (maximising exergy), developed some 10 years ago, was based on these observations and insights, to make resource use calculable in terms of land and time. In other words, how much land over time is required to capture solar energy to live from those self-reorganising (organic) resources? Or how much land is required to collect solar energy to compensate/recover from that exhaustive resource use, the part that we often refer to as ‘non-renewable’ [12]?

At least, that’s how non-organic resources are usually framed, as non-renewable. However, this framing leads to an unequal comparison in evaluating resource use: one kind includes restoring organic stocks, while restoring non organics are exempted from this bookkeeping. This is characterised as ‘resource discrimination’ [13]. The maxergy approach solves this by calculating what it takes to restore the original stock of used resources, of any kind (with renewables based on energy input) [14]. This approach is expressed as circular energy: the energy required for exergy recovery, or entropy reduction, via a land-sun conversion route.\(^3\)

This seemed to be a more easy and practical way to calculate and value the closing of cycles. It was certainly easier than other attempts, such as by Odum. However, thinking one step further, and with Bardi in mind, everything is in fact flowing and renewable. Everything renews itself on Earth, even non-growing substances such as metals. Only, whereas the cycle for organic materials is counted in years or decades, for inorganic materials it is millions of years.

Both kinds of flows are naturally restored, related to the unique situation on the Earth: on the one hand, the specific position of the Earth in relation to its nuclear power source, the sun, and on the other hand the young state of the planet, on its way to equilibrium but with enough energy in its core to modify, renew and reorganise the resources, the land and its composition.

The original maxergy calculation at first looked like a logical and practical approach, but for many it is not the easiest to understand, as I understood from people’s reactions. With these new insights, the question arises if this can lead to a more comprehensive way of calculating—not to figure how it all came about (Odum), or how the loss can be recovered (original maxergy), but to calculate what is currently still formed, or annually added, to the Earth’s stock in concentrated form. The naturally continuing flow could, in fact, be seen as our annual budget or ‘income’. Perhaps that would be a more understandable route.

Ergo, the hypothesis is: Any material is renewable, and is renewed, as long as you use less than is renewed over time.

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\(^3\)This ‘circular energy’ has been calculated by starting from re-concentrating material from the diluted background, such as dissolved iron ions in seawater for example, by filtering that seawater. The filtering out of the so-called thermodynamic reference background is a difficult concept for understanding the method. “Who is going to filter iron ions from the oceans?” is the usual response; surely there is enough iron! Sure, there’s enough iron, and other metals, but their concentration is decreasing, and recovery must be performed. The seawater route may seem far-fetched but it is already practised: ocean water is filtered for drinking water (desalinisation), and attempts are being made to extract lithium from seawater [25,27].
Sometimes the renewal is fast, sometimes it is slow, and sometimes it is extremely slow. All resources are part of a continuously flowing process on Earth. And either they come in sufficient volume that humans can use (more or less) with impunity, or they grow so slowly that unless a huge amount of energy is put in, they cannot be used indefinitely at current consumption levels. The ‘renewal time’ can extend to millions of years, as in coal formation or metal depositions due to volcanism, for example.

2. Characterisation of resources
Following the argument of natural flows, we can characterise resources under similar conditions.

The first category includes those substances with the shortest renewal time, namely the ‘regrowables’ such as plants. The second category is the streaming resources or ‘streamers’, such as clay. These are not regrowable but have relatively fast renewing flows due to erosion processes. They originate from mountain ranges that are worn down by wind and water but are in turn pushed up again by tectonic forces. The process may not be very fast, but it still provides a considerable and continuous volume flow. And it is of course speed multiplied by volume that determines the possibilities and potentials. For example, clay coming down in rivers can be used for adobe or, with extra energy input, as bricks for construction.

And as long as the use of loam, directly or by industry, is no more than what is available via rivers on a yearly basis, it is a continuous stream, or a material that ‘regenerates itself’. It is a flow maintainable for ages.

The first category, the solar driven regrowables, is mainly powered by solar energy. The second category, the streamers, is a hybrid: renewing via solar-derived wind and water erosion on the one hand, and on the other hand by activities of the Earth’s core to push up mountain ranges. (This is in addition to secondary energy inputs to treat them.)

The third group consists of the extremely slow ‘renewers’ (the ‘sluggish resources’) such as metals. These are concentrated depositions that come from the Earth’s core via tectonic action or volcanism. However, this is a very, very slowly process, and the system cannot keep up with the rate at which humans are currently using these substances. It takes millions of years for them to be restored. In addition, it still requires a great deal of energy to actually extract these ores, filter out impurities and make them fit for human use. And these concentrations are declining rapidly at current rates of use. Yet they do not disappear from the Earth, but instead are dispersed as highly diluted and scattered dust in the background.

There is a fourth category as well: substances that do not occur naturally in the Earth. These are substances which we humans have created at the expense of a lot of energy and effort. These ‘man-made’ or synthetic resources come from existing molecules, but are reorganised and combined into synthetics such as plastics which come mostly from oil, and thus belong in the third category.

All this leads to the following categorisation of available raw materials (although not yet products, which may require additional and significant energy inputs).
Table 1. The four types of resources and how they are renewed.

| Category                | Energy Basis                                  | Examples                           |
|-------------------------|-----------------------------------------------|------------------------------------|
| 1: Solar (-driven)      | land-sun-labour                               | wood, bamboo, hemp, flax, straw, rapeseed |
| (Regrowable resources, biobased) |                                               |                                    |
| 2: Streaming            | Sun-wind-erosion-gravity-earth activity-labour | loam, sand, pebbles, rocks, stone  |
| (renewed, flowing)      |                                               |                                    |
| 3: Sluggish             | Energy-earth activity-labour                  | ores, minerals, metals, fossil fuels |
| (very slow streaming, depleting) |                                              |                                    |
| 4: Synthetic            | energy-chemistry                              | PVC, PPE                           |
| (artificial, non-naturally formed, not streaming) |                              |                                    |

The question is, can we put numbers on for their renewal time? Which is explored in the next section.

2.1. Category 1: ‘Solar’ resources - Regrowables
The figures in this category are fairly well known: a forest supplies between 6 and 8 m³ of wood per hectare per year, or between 3 and 5 tons annually. Other crops are in the same range, somewhere between 1 and 10 tons/ha-year⁴.

2.2. Category 2: Streaming resources
To get a first indication of flow renewability, let’s analyse the use of loam or clay for bricks. Sediment reaches the Netherlands from rivers [15,16]. The Rhine has a ‘sediment load’ upon entry into the Netherlands of 3.25 million tons/year (plus an additional 0.9 Mt soil load coming from land—an intermediate point which had previously received the sediment as erosion dust from wind and rain). Those 4.15 Mt come mainly from the Alps, but in fact can be counted as coming from the entire water catchment area, which is approximately 168,000 km² for the Rhine [17,18].

Suppose Germany has already extracted its part of the Rhine sediment flow, then the part that enters the Netherlands can be entirely allocated for use in the Dutch land area. In addition, the river Meuse contributes a further 0.4 megatons, yielding a total of 4.55 Mt for 33,800 km² of land (being the land area of the Netherlands). Averaged over all the land, the process creates 1.35 tons per hectare per year of sediment for the Netherlands on a continuous basis! That is the flow rate of loam through its cycle.⁵

2.3. Category 3: Sluggish resources
2.3.1. Oil. The flow rate of fossil fuels has previously been explored [19]. For example, oil was calculated in People vs Resources [13]. Its assumed it took about 60 million years to produce all the oil that has been consumed and known to still exist. Dividing this total means that the ‘growth’ of oil over time is roughly 14,000 litres per year, worldwide. A litre of oil weighs about one kilogram, so 14,000 litres is 14,000,000 grams. Dividing this amount by the Earth’s surface of 510 million km² gives an annual production rate per square kilometre of 0.027 grams, which is about the weight of one drop (≈0.02 grams). In other words, every year, each hectare produces one hundredth of a drop of oil.

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⁴ Potatoes can deliver up to 50 tons per hectare, but that is not their natural growth. This yield is achieved due to the addition of other substances from within the system, such as pesticides and fertilisers, which decreases the EROI, or energy return on investment [20]. And so the system loses quality more quickly from within, for a short-term increased output. The same holds for greenhouse cultivation. On average in the Netherlands, six times more energy is used as input than the food energy which comes as output [26,28].

⁵ Even better would be to take all sediment divided over the total catchment area including mountain regions, but these data were not yet available.
Another and more direct resource is also conceivable here: bio-fuels, or oil from rapeseed, for example. This gives a higher yield than the natural boiling and pressing process of biomass in the Earth’s crust that lasts millions of years. From rapeseed we can calculate the harvest per hectare per year, which after processing yields about **700 litres per ha-year** (from 4 tons of rapeseed per hectare per year and after deducting inputs) [20].

It’s obvious that for fossil oil we have long ago passed the threshold of use in balance with the natural flow/growth. Duke’s estimate was we passed that threshold back in 1888 [21]. The rapeseed route provides a more realistic option, one also related to direct land use, which humans can assist in regeneration and balancing with the system.

2.3.2. **Iron.** Would it be possible to calculate a flow of iron ore stock forming? The route via volcanic and tectonic processes, seems somewhat complex and unworkable. However a possible approach is a estimated calculation by a simplified route: iron deposits along water flows, so-called ‘primal banks’ as were used for steel in the Middle Ages. There is some data showing that the formation of primordial iron needs only a few decades for serious depositions via the groundwater route [22,23].

The experimenters found that to extract one kilogram of usable iron from these river banks, about 13 kilograms of iron ore and 130 kilograms of charcoal were needed. To make 130 kg of charcoal, 760 kg of oak were needed. This amount is roughly equivalent to two or three oak trees.

In other words: 1 kg of iron = 760 kg of oak wood = 2 to 3 trees. In a Wageningen university report we find: “When those figures are translated into the amount of iron ore that was processed in the ‘Achterhoek region’ between 1700 and 1900, 200 years, we arrive at approximately 450,000 tons” [24].

All that data combined yields the following approximate picture:

Suppose that this processed ‘primal ore’ came from deposits in the ‘Achterhoek’ and surrounding region: the ‘eastern Netherlands’, namely Groningen, Friesland, Overijssel, Drenthe and Gelderland, totalling 16,500 km² (Limburg had its own primal banks), and that half of this growth was in ‘decades’ (and that the rest was older accretion—as stocks). In that case, 225,000 tons would have grown in that area of 16,500 km², which comes down to 136 kg per hectare every 200 years, which is 0.7 kg per ha-year. So that is the speed, or the space-time, of iron deposit renewability! To complete the picture, that is for the source. To make it available as concentrated stock, it needs processing with the above-noted 2-3 oak trees. Suppose these grow in 100 years, and there are 200 per hectare, and we need 2 trees to get that available 0.7 kg of iron, then that requires 1 ha-year of space time. The 0.7 kg is in fact a result from a 2 hectare-year yield, or effectively **0.35 kg/ha-year**. (And that’s not counting ore losses in the process.)

Now we have our first estimated reference for annual growth: the flow rate of iron per hectare! But this figure must be regarded as a maximum, because it is still wildly optimistic. The true yield is probably much less because there is a limited number of sites, and large stocks have probably built up over a much longer period of time. And anyway, the large deposits of mineral iron that come from tectonics and volcanic action have a much slower process. But this elementary calculation provides us with a first reference measure. If we were to stay below that, a huge step would have been made in the balanced use of raw metals.

2.4. **Category 4: Synthetics**

Plastics come from oil, and so we can use the same figures for their source, supplemented with a much higher secondary energy input to convert them from oil into those plastics in the second step. (Or we can use the renewable raw material route—bio-oil from rapeseed, for example.) We don’t need to give further details in this exploration.

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6 And for those primal river deposits, the country also has to be in pristine condition. The Netherlands is now being overhauled every 30 years, so primal ores do not get a chance to form.
3. **Summing up**

With all these findings we can specify the table and, among other things, add the ‘renewal’ or flow rate:

| Category | Energy Basis | Examples | Flow rate | Energy input | EE range | CO2 effect      |
|----------|--------------|----------|-----------|--------------|----------|----------------|
| 1: Solar resources (organically regrown, biobased) | land-sun-labour | wood, bamboo, hemp flax, straw, rapeseed | Normal: 2–20 ton/ha-year | limited | 0–10 MJ | Positive-neutral |
| 2: Streaming resources (renewed, flowing, hybrid) | Wind-erosion-gravity-earth activity-labour | loam, sand, pebbles, stone | Low: 1–2 ton/ha-year | average | 5–30 MJ | Neutral-little negative 0.5–4 kg/kg |
| 3: Sluggish/slow resources (geological renewed, extremely slow forming, depleting) | Energy-earth activity-labour | minerals, metals, fossil energy | Extremely low: 0–1 kg/ha-year | high | 20–220 MJ | Negative 3–30 kg/kg |
| 4: Synthetic resources (inorganic, not flowing) | energy-chemistry | PVC, PPE | Very low: < 1 kg/ha-year | high | 60–140 MJ | Negative 9–20 kg/kg |

This approach, of renewability of all substances, seems workable. It will still have to be determined for many other raw materials what that flow rate is, even if it is approximate. But this makes calculations much easier and more understandable. With this approach the link to space-time or land/solar potential can be made directly.

4. **Discussion**

Everything is renewable and is being renewed—at least on this planet: that’s because of the special circumstance that Earth’s core still bubbles and fizzes (as other planets might do as well), but that the sun sends a portion of its energy towards this planet every day in just the right amount. So far this discussion has been a theoretical analysis of resource flows, not meant to provide instant solutions.

Yet the point of all this argument is that we are miscalculating resource impact in evaluating our buildings (and other services as well). Minerals and metals get a disproportionate advantage by being considered non-renewable. The analysis shows that both types of resource can indeed be put under the same denominator and compared on the basis of renewability. The result will be that the choice for regrowable materials will be greatly strengthened, resulting in a much smaller impact and a huge decrease in CO2 emissions.

Given these findings, it is obvious that we need a new approach for construction, the world’s largest user of resources. Such a new approach would optimise for the renewability of resources in designing, constructing and maintaining buildings. This trend towards ‘biobased building’ has already kicked off. However, with these findings it should be obvious that it’s not only about a partial switch to some ‘renewable’ resources, but it requires a complete turnaround in the way we treat and use all our resources, and to stay within their natural regeneration capacity, i.e., the flow potential available in time and space. This is necessary in order to reduce CO2 emissions for energy input in high-embodied energy materials and at the same time avoid depletion of resource stocks, of any kind.

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7 However, if the use of a resource exceeds the natural flow rate, it is still necessary to calculate with re-concentration, this time human-induced—i.e., to once again add Circular Energy (from the 2.0 version) to the equation!
The calculations show clearly that we not only need a transition to renewable energy, but also a transition towards renewable materials, those that fall under Categories 1 and 2. At the same time we must stay within the limits of yearly flow rates of these resources.

How to implement this has to be further investigated, but a few directions can be given:

1. These data should be implemented in LCA’s to put closing cycles at the heart of evaluations, and work with real objective values, unweighted.

2. Practical: without much calculating, it’s obvious that metals should be avoided where possible.
   1) They must be biobased, or plant based by definition, and
   2) Use metals only when really unavoidable. That is, if no alternative solution can be found, and the function required is an inescapable necessity.
   3) Or use Category 3 resources only if it can be proven that to invest renewable energy will be paid back by increased effectiveness and long lasting performance by the provided service, saving more renewable energy than otherwise needed.

And even then the user should reserve the space required for regenerating.

3. This changes the general notion of circular, as practised in the circular economy. The definition and approach should be adapted, as described below.

5. **Conclusion**

It can be concluded that the hypothesis is true, everything is renewable, and is renewed in a certain volume in a certain time, with different underlying energy supply processes, direct or indirect, fast or slow.

If we don’t use more than the yearly added potentials, true sustainability and maintainability of resource use can be established. Take for instance iron: every year a maximum of 35 million tons of iron is added and available globally, through different geophysical processes. For reference, current use is about 2,160 million tons of ore, a factor of 60 times. To calculate just one example of the consequences and application: The potential iron yield is 0.7 kg/ha-year (excluding embodied energy). In the Netherlands, around 0.2 hectare is available per person. Within circular system boundaries, and over a lifetime of 75 years, a maximum total of 10.5 kg of iron is available per capita, or one bicycle per person.

In terms of buildings, that amounts to a few door hinges and locks.

Metals are framed as being non-renewable, but only because we use more of them than are being renewed. The same applies to all raw materials. This also sheds a new light on the usual illustration for a circular economy with a bio and a techno cycle. There is no such thing as a techno cycle, nor do exist non-renewable resources.: all are renewed, even if they follow different routes. Technocycle is just a word expressing high level of processing, high level of energy input, and neglecting regeneration.

At best we could say that organics are part of a biocycle, and minerals and metals are part of a Geocycle! Figure 1 below illustrates the yearly flow of resources (as denoted by the thicker yellow line), embodied energy and CO2 emissions are the opposite of line thickness.

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8 It’s not enough to address renewability only: raw materials concentrated by the Earth system are in most cases not immediately usable. Lots of energy still has to be invested to (de-) form them, to make products from them. (see Column 6 in Table 2). This so-called ‘embodied energy’ must also be of renewable origin. Or at least it must fit back into the natural flows over time. (Incidentally, the embodied energy figures given here are often primary input; many kinds of secondary inputs are usually not included, so the real figures are much higher.)
6. **Significance and urgency**

For far too long we have parasited on the historically available capacity of the Earth’s system, depleting its stocks and lowering its capacity to absorb waste and harmful emissions. We are only kidding ourselves with the paradigm that something like non-renewable resources exist. We will face major disruptions in the Earth’s climate and resources stocks, and it’s of utmost importance to get our calculations right not to worsen the situation.

With 8 billion people sharing this planet, it’s about time we take responsibility and adapt to our true potential and stay within the capacity of closed cycles with all resources.

If a resource is not renewed, it's worthless.

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