A First Natural Science Sustainability Theory: Entropy as a Criterion for Sustainability

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Abstract:
Three factors motivated the development of the concept presented in the lecture[1], on which this article is based: “Sustainability” has become a term that is overused and, for the most part, misappropriated for political and commercial marketing purposes.
- Thermodynamics, and especially entropy, are understood only to a very limited extent and mostly incorrectly; non-equilibrium thermodynamics is virtually unknown, even among natural scientists.
- In climate research and the discussion surrounding climate stabilization measures, thermodynamics plays virtually no role.

It will be demonstrated how entropy can be understood and communicated in a very practical way within the framework of non-equilibrium thermodynamics. On this basis, a comprehensively defined theory of sustainability—the preservation of the Earth’s life-support systems—will be presented: a first natural-science-based sustainability theory; its core is the use of entropy as the criterion for sustainability. The criterion is objective, and the results are falsifiable after applying the criterion. The criterion is applied as an example to several major technological processes. Furthermore, it is shown that
- “climate-neutral” does not automatically mean “sustainable”;
- technological measures for climate stabilization (reducing atmospheric CO_2 concentrations) are extremely unsustainable.

Sustainable approaches (natural and renaturalized ecosystems as well as organic farming) are briefly discussed. Further reading can be found in the references.

Keywords

sustainability, thermodynamics, non-equilibrium thermodynamics, entropy, climate change, species decline

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[1] Lecture presented at the Leibniz Society of Sciences on March 12, 2026 /presentation available here: https://www.bernhard-wessling.com/vortrag_entropie_nachhaltigkeit_ls (German)

1. Background

Since the early 1990s, the term “sustainability” has been used with increasing frequency. Today, it is sometimes used as a buzzword—devoid of meaning—in advertising for products and services, as well as for political programs and decisions. In most cases, no justification is even provided as to how the subject of the advertisement is sustainable.

The first attempt to define the term was made in the so-called Brundtland Report of the United Nations in 1987 (United Nations General Assembly 1987). There, it is understood in a distinctly anthropocentric way: the goal is to meet the peoples’ needs—which are themselves described in vague terms—including those of future generations. In 2015, this was further defined through the 17 “Sustainable Development Goals.”[2] However, even within the respective chapters, the definition does not become much more precise.

Despite all efforts using life cycle assessments and “life cycle analyses,” there has been no scientific theory of sustainability to date (as Obura et al. 2026 explain), nor any overarching criterion that comprehensively describes all forms of environmental consumption and allows sustainability to be objectively measured and compared—not even through valuation in monetary terms.[3] However, in their publication, they themselves do not present a theory (at least not in the scientific sense), but rather another purely qualitative model; nevertheless, this model does at least state as a prerequisite for achieving sustainability goals that nature’s capabilities and functions, as well as the Earth’s resources, must be preserved.

The authors of a review article on life-cycle assessments note that these are highly complex, encompass a vast number of categories, and thus make a conclusive, summary evaluation difficult. They are therefore searching for a single eco-index, which, in their opinion, can be—or should be—found in pricing (“yen,” the Japanese currency). However, these—like other eco-indices—always require the subjectively colored judgment of expert panels. In the case of the “yen” (or euro) as an index, such a panel would attempt to describe peoples’ (presumed) willingness to pay.

The first quantitative targets were formulated in 2009 in the form of “planetary boundaries” (Rockström, Steffen, Schellnhuber et al., 2009), which were further developed a few years later (Steffen et al., 2015). The table below presents the descriptions and values (summarized by the author). It is very valuable for public discourse to have such scientifically developed and debatable planetary boundaries defined. However, even these are not operational in the sense that they could help assess, prior to the introduction of products or processes, which ones are more sustainable or less unsustainable than their alternatives.

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[2] https://sdgs.un.org/goals These 17 goals are: 1 No Poverty, 2 Zero Hunger, 3 Good Health and Well-being, 4 Quality Education, 5 Gender Equality, 6 Clean Water and Sanitation, 7 Affordable and Clean Energy, 8 Decent Work and Economic Growth, 9 Industry, Innovation, and Infrastructure, 10 Reduced Inequalities, 11 Sustainable Cities and Communities, 12 Responsible Consumption and Production, 13 Climate Action, 14 Life Below Water, 15 Life on Land, 16 Peace, Justice, and Strong Institutions, 17 Partnerships for the Goals

[3] Obura et al. (2026) wrote: ***“Although sustainable development is an agreed-upon vision for all countries, it lacks a theoretical foundation.”*** Poritosh et al. (2009) attempted to establish a general sustainability criterion by quantifying ecological values in yen; however, such an assessment is subjective because it is based on a willingness to pay estimated by expert panels.

Earth System Process	**Control variables**	**Planetary boundary**	**Current status[4] (2015 value)**
Climate Change	CO_2 concentration (ppm) Energy imbalance in the upper atmosphere	350 ppm CO_2 +1 W/m²	423 (398.5) +2.97 (2.3)
Change in biosphere integrity	Extinction rate per 1 million species Biodiversity Integrity Index (BII)[5]	<10 extinctions per 1 million Maintain BII at >90%	>100 (100–1,000) (84%)
Depletion of the stratospheric ozone layer	O_3concentration, DU[6]	<5% decrease from the preindustrial level of 290 DU	Exceeded over Antarctica
Ocean acidification	Average carbonate ion concentration	≥80% of pre-industrial levels	(~84%)
Biogeochemical cycles: (P and N cycles)	P flux into the ocean N flux	11 Tg P/year 62 Tg N/year	4.4 (exceeded regionally) 165 (22)
Change in land use system	% of forest area compared to the original vegetation cover	0.75	59 (62)
Freshwater consumption	maximum volume in km³/year	4,000 km³/year / 12.9%[7]	22.6%
Atmospheric aerosol pollution	Optical aerosol depth, regional	0.25 AOD	(0.3)
Introduction of new chemicals	No definition of control variables yet	-[8]	-

Table: Simplified, summarized content of Table 1 in Steffen et al. (2015); Running (2012) had proposed the human appropriation of the terrestrial plant production as a more comprehensive and basic planetary boundary.

It would therefore be sensible and very helpful for the discussion—and especially for technical and political decisions—if a theory grounded purely in the natural sciences could be developed that includes a criterion for assessing the degree of sustainability of processes or products in comparison to alternatives.

Such a criterion must be able to quantitatively describe the consumption of environmental resources of all kinds. To this end, the productivity of nature—and thus biodiversity—must also be taken into account. A fundamental problem is currently evident: Everything related to climate change receives about 100 times more attention than anything related to species loss. However, if one objectively considers the severity of the two crises, it would be clear that both crises should receive roughly the same level of attention—and not just attention, but above all investment of personnel, time, and money in research, development, and the implementation of solutions to these crises.

And it must be clear: No measures to solve one crisis should be taken that could neglect—or even exacerbate—the other crisis. A criterion for sustainability that is urgently needed must be able to determine whether a particular measure to solve a crisis carries such a risk or not.

Compounding the problem for some time now is the fact that climate neutrality has come to be practically equated with sustainability: Anything that can be operated, used, or produced without CO_2 emissions—even if only "net"—is quickly declared sustainable. Just how questionable this is can be seen, for example, in the production and combustion of "bio"gas and in the supposedly climate-neutral use of wood for heating: The impact on soils and biodiversity—and, in the case of wood combustion, the emission of hazardous air pollutants—is ignored.

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[4] This column provides updated values—not those for 2014/2015, but rather those for 2025; see https://publications.pik-potsdam.de/rest/items/item_32589_5/component/file_33151/content (in parentheses: value according to the 2015 report)

[5] This index is used to assess the functional ecosystem diversity of regions and was developed by the Natural History Museum, UK: https://www.nhm.ac.uk/our-science/services/data/biodiversity-intactness-index.html

[6] DU: Dobson unit, see https://en.wikipedia.org/wiki/Dobson_unit

[7] The units were modified according to [4]to % of ice-free land area with significant variations in water availability (wet or dry)

[8] This was updated according to(4) to monitor the "percentage of synthetic chemicals released into the environment without adequate safety testing," but no figures are available yet, except for the notation ">0"

2. Starting Point for the Search for Such a Criterion

A suitable sustainability theory can best be sought in thermodynamics, particularly by incorporating Prigogine’s non-equilibrium thermodynamics. This makes sense because all processes in the world that interest us in the context of sustainability require or involve the conversion of energy and matter. And processes involving the exchange of energy and matter are precisely the core of thermodynamics.

It is particularly important to note the following: Since we want to preserve nature’s capabilities and functions as well as the Earth’s resources, we must recognize what is essential about nature. It is the fact that countless material components have self-organized—that is, without any external directing influence—into so-called “dissipative structures” (a term coined by Ilya Prigogine, the founder of non-equilibrium thermodynamics and a Nobel laureate, as recognized by the Nobel Committee in 1977). The smallest (single-celled organisms) as well as small and larger such structures (multicellular organisms and living beings) form communities (ecosystems) in which—and from which—we humans also live. We have additionally developed societies with infrastructure and interconnected economic systems. All of this constitutes complexity (see Weßling 2025).

It arises in open systems that, due to a supercritical high energy input, are far from thermodynamic equilibrium. These systems develop complex dissipative structures, accompanied by entropy export. Complex structures are characterized by the fact that they exhibit patterns but lack the regularity found in crystals with their unit cells (which exhibit “order”); complex structures cannot be described by a more or less simple algorithm. They are each unique in detail, whether they are galaxies, tree canopies with their branches, or snowflakes (examples in B. Wessling 2026a).
It is extremely regrettable—and it hinders a comprehensive approach to a non-equilibrium thermodynamic analysis of current environmental crises—that this modern thermodynamics is completely absent from general education (e.g., in the form of popular science books) and almost entirely absent from university education. It is therefore not surprising that entropy is widely misunderstood—either not at all or incorrectly and one-sidedly—as an indicator of disorder. Added to this is the confusion caused by the use of the term “entropy” for entirely different phenomena in information theory and quantum physics. Entropy must be understood purely thermodynamically, in the sense of Prigogine.

3. Proposal for Discussion: Entropy as a Criterion for Sustainability—the Core of a Scientific Theory of Sustainability

This leads to my theory of a unified, universally valid criterion of sustainability: entropy. I have been presenting this for discussion since 2023/2024, including here as a summary of my lecture on March 12, 2026.[1]

Entropy is an indicator of the loss of energy’s value (and that of matter, which is also energy or contains it). The less usable a form of energy is, the more entropy it contains. This can be clearly seen in the case of heat: A high-temperature heat source enables the generation of electricity; lower-temperature sources can be used to heat homes to comfortable temperatures; air at -20°C and even at -90°C still contains heat—but this is a form of energy that is no longer usable (for us or in nature).

The sun provides the Earth with *energy*; it radiates back practically the same amount as entropy, in the form of long-wavelength infrared radiation. This has an effective temperature of approximately -18°C (Penn State College). Humankind has been using coal as a fuel since the Bronze Age—that is, for about 3,700 years (GEO Wissen 2023). The smelting of copper (using charcoal) dates back even further. With the use of coal and ore, humankind began to exploit *environmental capital*. The consumption of environmental resources of all kinds leads to the production of entropy. This also applies to complex dissipative structures (ecosystems): When these are damaged or destroyed, or when biodiversity is reduced, this corresponds to an increase in entropy (because, conversely, the formation of these complex structures corresponded to a reduction in entropy, which was exported into space in the form of long-wave infrared radiation).

Ultimately, entropy manifests itself not only in the form of waste heat, but also materially in the form of waste of all kinds (ash, tailings from coal and ore mining, household and industrial waste). The essence of this entropy-based criterion of sustainability is as follows: Product or process A, which—compared to more or less comparable alternatives B, C, D …—produces less (non-radiative) entropy or has a lower “negative” entropy balance, is to be regarded as more sustainable; more precisely, as less unsustainable. The following clarifications are necessary in this regard:

1) As long as humanity requires non-renewable raw materials to manufacture machines, products, and infrastructure (which always requires energy), it cannot truly operate in a sustainable manner over the long term. At present, we can only determine which processes or products are less unsustainable compared to their respective alternatives.

2) The entropy balance of a process (or a series of processes culminating in a finished product) consists, on the one hand, of effects through which entropy is exported; this is mathematically negative but should be regarded in the assessment as *an entropy benefit* (positive); on the other hand, in order to export entropy from a system, a great deal of energy must inevitably be expended, which causes a high level of entropy production. Added to this is the material consumption directly and indirectly associated with the processes: this, too, causes entropy production.

Industry, transportation, and households generate, in addition to waste heat, primarily non-radiable forms of entropy—partially in the form of waste, and partially in the form of the destruction of functioning, useful, high-value complexity. This entropy is recorded in an entropy balance with a positive sign (increase in entropy), but is considered negative in the assessment (*entropy damage*).

Ultimately, for non-sustainable processes to be as minimal as possible, it is essential to achieve a high level of (radiable) entropy export and, in addition, to generate as little non-radiable entropy as possible. However, the balance will always be nominally (mathematically) positive; more non-radiable entropy (*entropy damage*) is generated than radiable entropy combined with (radiable) entropy export (*entropy benefit*). Overall, we assess the (usually drastic) surplus of *entropy damage* as negative from a sustainability perspective.

3) Especially in the early stages of applying the entropy criterion, it will be difficult—due to a lack of data and insufficient research and computational capacity—to compile reasonably complete entropy balances, even if one limits oneself to the major entropy contributions. To this end, I propose using the MIPS (Material Intensity per Service Unit) metric developed by the Wuppertal Institute in the 1980s and 1990s (Schmidt-Bleek 1993). It is an excellent indicator of entropy production, as it captures and sums up the total material flows for a raw material (and thus, ultimately, for a complete product), including water and air. Data for a wide variety of raw materials and energy sources can be found here (Wuppertal Institute). Even when applying MIPS (in metric tons per service unit), the result is clear: the process with the lower index is less unsustainable.

4) Both the entropy criterion and the coarser-resolution MIPS represent a quantitative, objective, and at the same time falsifiable assessment of sustainability (or unsustainability). This is an enormous advantage over eco-balances and life cycle assessments, which often use categories that do not align—even for comparable processes or products. For example, how should one assess the difference in sustainability between a process powered by solar energy and one powered by

hydrogen (generated using PV electricity) or biogas? The corresponding life cycle assessments sometimes use completely different categories, and a final assessment always requires subjective judgments regarding which category is considered more significant in terms of sustainability compared to the others.

4. Application Examples

This section will only briefly outline which examples were presented quantitatively and with what results, but will not cover the data set selected for this purpose or the calculation methods used. An overview of this can be found in the presentation itself[1],and in detail in the books to be published in late 2026 (Wessling 2026c). Among other topics, the following have been analyzed in greater detail to date:

- Corrosion and corrosion protection: On average, 3.4% of the gross national product is lost worldwide each year due to corrosion. The entropy production per metric ton of lost (corroded) steel (more than 68.22 MJ/K (20 °C) per metric ton of crude steel, due to energy consumption, i.e., approx. 4.1 EJ/K (EJ: exajoule, 10^{18} J) per year for approximately 60 million metric tons worldwide, can be reduced by a factor of up to 10 if the novel “passivation by the Organic Metal” technology developed by the author (Wessling 2010, Wessling 1999) were to be implemented.

- After finished production of bare **printed circuit boards**, and before electronic components are placed and soldered onto them in automated systems, these PCBs require a **final surface treatment** that protects the exposed copper contact points from oxidation and ensures the **solderability** necessary for subsequent assembly. To this end, the author, together with teams at his company, developed a technology also based on the Organic Metal (Wessling 1999b) and successfully introduced it, the OMCSN technology, to the global market. This made it possible to partially replace a lead-based process (which is environmentally toxic and increasingly unsuitable for modern printed circuit boards) and, to a greater extent, a final surface coating consisting of micrometer-thin layers of nickel and gold with this process. The MIPS analysis yielded the following results per m² of coated copper surface (corresponding to approximately 10 m² of printed circuit board area):
a) 1.6 metric tons of material movement for nickel/gold
b) for the new OMCSN technology (introduced to the market in the early 2000s): 0.142 metric tons, which corresponds to a reduction by a factor of more than 11 to 8.9% of the previous environmental impact.

For the approximately 20 million m² of coated printed circuit boards on the market annually using this new process, this corresponds to a material consumption (and corresponding environmental impact) of 284,000 metric tons; if these printed circuit boards were coated with nickel/gold, the figure would be 3.4 million metric tons.

- An even **greater *reduction in environmental impact*** would have been possible through the industrially proven further development of a coating that is only nominally 50 nanometers thick (Wessling 2007). This would reduce the MIPS value to just 327 grams per m² of copper surface area, corresponding to 0.02% of the environmental impact caused by nickel/gold or 0.23% of that caused by OMCSN. For reasons that are unacceptable from both a technical and economic standpoint—and which cannot be explained here—the buyer of the author’s company did not implement this technology, despite its acceptance by early customers.

- Research is being conducted worldwide on an **iron-based energy “cycle” economy** (Debiagi et al., 2022; Neumann et al., 2024). This is purported to be a climate-neutral and sustainable solution to the problem of unreliable and unevenly available renewable energy (sun, wind), thereby eliminating the need for gas-fired power plants. To achieve this, iron powder is to be burned in previously coal-fired power plants that are to be converted (and would otherwise be decommissioned); the resulting iron oxide powder is to be shipped to North Africa (into the Sahara desert) and reduced back to iron powder using hydrogen generated there in large solar power plants. The entropy analysis shows that producing a net 700 kWh of electricity (after deducting the electricity consumed by the PV plant to generate$_{H_2}$) from 1 metric ton of iron powder would “cost” 29 MJ/K in entropy production; by contrast, the direct use of the generated PV electricity would cause only 3 MJ/K of entropy. This demonstrates that the argument that this technology is sustainable because it is allegedly climate-neutral and the required energy is generated from renewable sources is not valid: a by 26 MJ/K higher entropy amount—that is, nearly 10 times greater entropy production—is significantly less sustainable, drastically more unsustainable.

- **“Direct air capture” (DAC) for removing CO_2 from the atmosphere** requires three times as much energy as the usable energy provided by the combustion of, for example, natural gas. However, compared to the reduction in entropy in the atmosphere (entropy benefit of DAC: 4.15 MJ/K per metric ton of CO_2), entropy is produced at a rate of 23 MJ/K (entropy damage from DAC)—almost six times as much damage as benefit. This also demonstrates just how unsustainable these technologies are.
- In addition, various geoengineering approaches were examined, all of which are blatantly unsustainable (injecting SO_2 into the stratosphere; macroalgae farms in the ocean; grinding basalt and allowing it to weather). For more on this, see the presentation[1] and the forthcoming books (Wessling 2026c).

It is important to note that while entropy can indicate the total amount of environmental resources consumed (in the entropy unit J/K), it does not specify exactly which environmental resources these are. This can include everything from raw materials to landscape, soil, water, environmental pollution, species loss, and much more. In this respect, the entropy criterion cannot and should not replace other existing research methods (ecobalances, life-cycle assessments), but rather complement them and provide a summary assessment of these methods.

Entropy can be considered as a “price tag”, summarizing all the various cost components of a total price (just like also we, when buying goods, do not analyze which cost components in detail are responsible for the resulting total price, we just copare prices). Entropy is the currency which we are using when dealing with the environment.

5. The Alternative: Natural Processes

Climate change and species loss must be addressed simultaneously and using the same approaches. This is the only truly sustainable alternative. The fundamentals for this can be found here (for more details, see Wessling 2026a, b, c):

a) Processes in the soil—when soils are allowed to develop a diverse vegetation cover and thrive without the use of pesticides or chemical fertilizers—enable the storage of enormous amounts of CO_2 in the form of ultimately stable mineral-organic complexes of carbon-containing compounds; this applies to organic farming as well as to mixed forests and, above all, to old-growth forests.

b) Peatlands and other wetlands store significantly more CO_2 than soils on biologically and organically managed cropland and pastureland are capable of; this also applies to ocean soils if—as UN member states have agreed for 2030—30% of the oceans are placed under protection; to date, 10.1% are protected, but this target was achieved five years late and largely concerns national rather than international marine areas (UNEP 2026).

c) The approaches outlined in a) and b) can not only mitigate, then halt, and ultimately reverse climate change in the long term, but they can also effectively address species decline: first slowing it down, then stopping it, and finally improving biodiversity again.

d) The entropy inevitably generated by all these processes is radiated away from Earth, with the exception of the entropy generated by humanity through the necessary technical interventions in renaturation processes (and through the near-natural agricultural and forestry use of land).

6. Further Research

The theory—presented in increasingly detailed form since 2023/2024 but still new—of using entropy as a quantitative, objective, and falsifiable criterion for sustainability naturally requires further research. Entropy and MIPS data, as well as calculation methods and capacities, must be deepened, broadened, and refined. Although the method can already identify clear trends, the quantitative findings are still too rough and incomplete for broad, socially productive, and environmentally effective application. This could be quickly improved with significantly greater human, financial, and computer-assisted research capacity. In doing so, it will also be possible to incorporate the necessary social aspects of sustainability.

Another worthwhile area of research is the application of entropy in economics. The book (Wessling 2026c) tentatively develops the idea that there are direct links between entropy, costs, and inflation—and thus with the financial system (here, too, social aspects can and must play a role). Thermodynamicists and economists should jointly explore this approach. This could lead to the development of a practically implementable concept for an “entropy economy”—a concept that goes far beyond earlier, rather rhetorical and declamatory mentions of entropy (which were ineffectively framed using the misleading concept of entropy from information theory) (Georgescu-Roegen 1971; Galbraith 2025) in the context of economics.

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