Entropy as Criterion for Sustainability
– Judging CCS / CCU as Unsustainable –

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Abstract

Non-equilibrium thermodynamics principles are briefly reviewed with focus on entropy. A new proposal is derived as a quantitative criterion for sustainability. It is then shown that CCS and CCU are not sustainable climate change mitigation processes.

Introduction

In the worldwide discussion on sustainable resource management, whether related to the biodiversity or the climate crisis, thermodynamics almost do not play any role, and even less non-equilibrium thermodynamics. While the latter thermodynamics and "entropy" are explained and referred to only very rarely books and papers about environmental topics (e.g. in the book "A New Ecology Systems Perspective"[1], which shows the principles of how ecosystems are developing and functioning), it is so far not used for evaluating sustainability of certain technological ecosystem management or climate change mitigation attempts. Here some first proposals for bridging this gap will be introduced.

2 A brief review: Non-equilibrium thermodynamics and dissipative structures

Non-equilibrium thermodynamics had fundamentally been developed by Ilya Prigogine, for which he received the Nobel Prize in 1977.[2] He described for the first time self-organization into complex

1 Nielsen, S., Fath, B., et al, *A New Ecology Systems Perspective*, 2nd edition, Elsevier Amsterdam, 2020

2 https://www.nobelprize.org/prizes/chemistry/1977/press-release/ with links to further sources

structures: "dissipative structures". "Dissipative" because open systems are far from equilibrium due to a supercritical energy input and cannot compensate ("dissipate") the energy flow other than by forming complex structures, which is associated with a strong entropy export into the environment, outside of the open system.

This becomes particularly vivid when looking at Bénard cells (Fig. 1). These are formed as soon as one heats a glass dish filled with oil (for better visibility it contains fine metal chips) from below and slowly increases the heat input. When a characteristic heat supply is exceeded, 5- and 6-cornered cells will suddenly be formed because the oil cannot *dissipate* the supercritical heat otherwise: The cells are synchronously rolling, thereby effectively dissipating the excess heat.

Fig. 1[3], Bénard cells

Prigogine also studied cyclic reactions in particular, including the Belousov-Zhabotinsky reaction. This reaction repeatedly forms complex patterns that each time look different in detail (Fig. 2).

Fig. 2[4], Belousov-Zhabotinsky reaction

According to Prigogine, this is due to the fact that a supercritical energy input forces an open system into a state far from equilibrium, exporting entropy. And this is the crucial point that fundamentally extends the conventional understanding based on classical equilibrium thermodynamics:

While in the scale of the whole universe entropy is constantly increasing and can only increase (2nd basic law of thermodynamics), this is not (necessarily) the case within an open system. Out of those,

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3 https://www.experimente.physik.uni-freiburg.de/Thermodynamik/waermeleitungundkonvektion/konvektion/benardkonvektionszellen; reprinted with kind permission of the Faculty of Physics of the University of Freiburg.

4 Photos and videos showing a typical reaction sequence: https://www.flickr.com/photos/nonlin/3572095252/in/album-72157623568997798/; reprinted courtesy of Stephen Morris (Univ. of Toronto, Canada) and Mike Rogers.

entropy can be exported, thus it is decreased - and a lower entropy content is, according to Boltzmann's statistical interpretation, identical with a higher degree of order.[5] The lower the entropy, the more complex the order: A regular crystal has a higher entropy than an oak crown, because in arbitrarily small or arbitrarily large neighboring volume segments to be compared, the system elements (here: the cells forming branches and bark) are all in a different place.

The reason for this is the fact that in all such non-equilibrium systems processes take place that are described with non-linear equations; And these processes also interact with each other, which makes the whole system to behave extremely non-linearly. In other words, it is in principle unpredictable how the non-linear processes, which still influence each other, will eventually play out. This leads to the fact that in the course of time, while the supercritical amount of energy (and possibly also matter) flows into the open system, "bifurcations" (as Prigogine called it) happen again and again: The system can unpredictably suddenly take a different course.

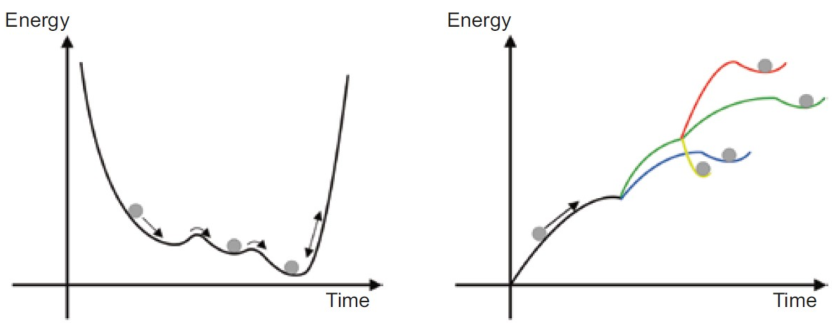

Fig. 3 shows schematically the principally different course of reversible processes leading to an equilibrium state (left), and in a non-equilibrium system (right) with irreversible processes, resp.

The (free) energy in equilibrium tends towards a minimum and corresponding processes occur spontaneously, are reversible, and the entropy reaches a maximum. Quite different in non-equilibrium: The energy influx is more or less continuous, the entropy reaches lower values, and after some bifurcation events relatively stable states can be reached, but they are mostly subject to decay if they are not stabilized with further energy inflow, processes and dissipative structure formation are irreversible. However, decay eventually taking place does not lead a state identical with the beginning of the process sequence, that’s impossible.

We know this from life, but it is often overlooked that "life" (e.g. organisms and ecosystems), but also inanimate dynamical systems like rivers, weather or galaxies, cannot be described by equilibrium, but only by non-equilibrium thermodynamics: Entropy is constantly exported from open dynamical systems (ultimately into the universe, there presumably into black holes), and the

5 in some papers and books, instead of saying „entropy export“, the term „negative entropy is used“; it was originally introduced by Erwin Schrödinger when writing „Living matter evades the decay to equilibrium. It feeds on 'negative entropy'“ and using this term several times, also when saying that an organism can only stay alive by „drawing [negative entropy] from its environment“ (E. Schrödinger, What Is Life? The Physical Aspect of the Living Cell; With Mind and Matter; & Autobiographical Sketches; Cambridge University Press 1944.). I prefer the expression „entropy export“ later introduced by Ilya Prigogine, because in reality, entropy is generated during the various processes *within* an open system like an organism (i.e., within the cells of said organism) and would be accumulated therein if not exported; exported by radiation of low temperature heat and by „export“ of waste materials; „waste“ meaning „not useful for said cell processes“, like oxygen in the case of plants’ photosynthesis, CO_2 in the case of animals’ breathing, also skin flakes, urine or feces.

processes are non-linear, interacting also still non-linearly with each other. Complexity and coincidence are thus very closely related. Non-equilibrium is what keeps us alive, "equilibrium is decay and death".[6]

3 Is that relevant for us? Yes, not only, but also as a criterion for sustainability

Some may think that these are rather theoretical considerations and that "entropy is at best interesting for an academic discussion" (which is what I occasionally get as an answer). This must be strongly contradicted. Basically, Prigogine's thermodynamics is another pillar for the understanding of our world on a par with the theory of relativity, quantum physics or the evolution theory. However, it is not perceived this way at all, it is already almost not common at universities, it is only very briefly dealt with in thermodynamics textbooks on little more than 20 pages, while equilibrium thermodynamics on the main 900 pages. This is despite the fact that in reality, apart e. g. from sugar water and alcohol diluted with water, there are hardly any equilibrium systems and processes in the real world, but the vast majority are non-equilibrium systems and processes: weather, climate, life, ecsystems, only to name a few. In chemical research and industrial practice, only non-equilibrium processes take place. Unlike the other three fundamentally important theoretical buildings, non-equilibrium thermodynamics is also not a topic of high school courses at all. And while one can find a sufficient number of popular science books and articles for different levels of prior education if one wants to learn about relativity, quantums or evolution, one will almost completely fail when searching for easy-to-understand books or articles on non-equilibrium thermodynamics or entropy.[7]Thus, our linguistic images have not evolved either: We constantly complain that something is "out of balance, out of equilibrium" (and wish it would be brought back into equilibrium, as if it had ever been there): Ecosystems, the climate, exchange rates, economy and the financial system in general. And the German Constitution demands to make sure that "the requirements of macroeconomic equilibrium" are taken into account.[8] Surprisingly, however, the so-called "equilibrium" is only maintained if the economy grows; even in the case of stagnation, i.e. zero growth, the equilibrium requirement is said to be no longer met. In fact, the economy is a complex non-equilibrium system and has never been in equilibrium (if in equilibrium, nothing would happen).

The fact that the world with us in it exists only because, fortunately, everything is NOT in equilibrium, but instead it moves in more or less stable dynamic processes far from equilibrium, is widely unknown. Likewise the meaning and the role of entropy is predominantly not understood.

In the current climate debate, there are more and more publications in various media about processes with which CO_2 can be removed from the atmosphere and either stored in deep layers of the earth or

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6 Ludwig von Bertalanffy, in the original the quote reads: *"Biologically, life is not maintenance or restoration of equilibrium but is essentially maintenance of disequilibria, as the doctrine of the organism as open system reveals. Reaching equilibrium means death and consequent decay."* in: "General Systems Theory, published by George Braziller, N. Y. 1968, p. 191". Bertalanffy is the creator of the term “steady state” which is not steady at all, and is a non-equilibrium system as well.

7 The book "What a coincidence! On Unpredictability, Complexity and the Nature of Time" (SpringerNature 2023) is a first attempt to fill this gap in a very easyly understandable and narrative form.

8 Art 109, para. 2 of the German Constitution reads (translated and highligted by the author): "The Federation and the Länder [States] shall jointly fulfill the obligations of the Federal Republic of Germany arising from legal acts of the European Community based on Article 104 of the Treaty establishing the European Community to observe budgetary discipline and, within this framework, shall take into account the **requirements of macroeconomic equilibrium.**"

used in chemical processes.[9] Investors and politicians are taking a serious look at this, a blatant example being "e-fuels".[10] Their energy demand and hence entropy generation for hydrogen production and carbon capture, followed by the synthesis of the is outstandingly high and can not seriously be called „sustainable“. Any electrically driven car is more sustainable by orders of magnitude. With a hypothetical product from CO_2, called "Dreamium™", the authors of a book[11] are showing that chemical use of CO_2 would contribute only unrealistically small amounts to the necessary reduction of CO_2 concentration, therefore, they are concluding, capture and storage are the only option.

All the various technological attempts are by no means reported without criticism, but the discussion is limited to risks[12] and costs. The energy requirement is often mentioned without comment, if at all; that this corresponds to four times compared to what we have been provided with in terms of usable energy (see below) when 1 ton of CO_2 was generated is not clear to the journalists, nor apparently to the operators, investors and politicians who decide on this. Nor that this would not change at all if "renewable energy" were provided for it: Neither do we have an infinite amount of it, nor can we harvest it for free (but need raw materials, space, water …, and dollars), and this energy conversion also creates a lot of entropy.

3.1 First assessment: Sustainability of CO_2 end storage?

In the following, we will first assess whether CO_2 final storage can be sustainable. There is a lot of publicity and advertising as if final storage is THE panacea against climate change. Furthermore we will deal with proposals for the utilization of CO_2, i.e. the conversion of CO_2 into useful raw materials (section 3.2).

3.1.1. energy estimation of final storage

We compare the enthalpy of formation of CO_2 with the energy needed to collect the gas and store it in deeper layers of the earth as $CaCO_3$: 1 ton of CO_2 contains 22,727 moles of CO_2 equals -8.9 million kJ enthalpy of formation (molar -393)[13], of which we were able to use less than one third (i.e., about 2 million kJ) as available electrical energy, the rest was (more or less used) heat and entropy.

M. Fasahi et al. published a techno-economic assessment of direct air capture plants.[14] As shown in their Table 1, according to literature and based on the level of heat integration, the overall heat demand is in the range of 1420–2250 kWh (thermic) per ton CO_2. The necessary electrical power is reported to be in the range of 366–764 kWh per ton CO_2. In the following we will use 2000 kWh_{th} and 600 kWh_{el} for discussion, Within the order of magnitude of these values, similar values can be found in various publications as well.

9 cf. https://en.wikipedia.org/wiki/Carbon_capture_and_storage, https://www.globalccsinstitute.com/, https://en.wikipedia.org/wiki/Carbon_capture_and_utilization, one example: https://www.nature.com/articles/s44160-022-00234-x, https://actionaidrecycling.org.uk/carbon-capture-utilisation-and-storage-effects-on-climate-change/

10 https://efuel-today.com/en/production-process-of-e-fuels/

11 “Introduction to Carbon Capture and Sequenstration”, the Berkeley Lectures on Energy, Vol. 1 https://www.worldscientific.com/worldscibooks/10.1142/p911#t=aboutBook

12 https://www.nature.com/articles/s41558-021-01175-7

13 https://www.seilnacht.com/Lexikon/dhtabell.htm

14 https://www.sciencedirect.com/science/article/pii/S0959652619307772

The necessary heat is equivalent to 7,2 Mio kJ (almost as much as the enthalpy of CO_2 formation!), but not delivered with 100% efficiency; if it can be provided with 80% efficiency, one has to start with 9 Mio kJ of primary energy which is thus equivalent to the enthalpy of formation. In addition, the necessary electricity is equivalent to 2,16 Mio kJ; taking the worldwide average coal power plant efficiency of 31%,[15] 7 Mio kJ primary energy needs to be provided and is consumed.

In total, 16 Mio kJ are necessary, which is almost twice as much as the CO_2 formation energy, hence the energy input is about 4 times higher as the amount of exergy (the available useable energy), which led to the formation of this said 1 ton CO_2.

The argument that one uses regenerative energy from the hot volcanic depths of Iceland or solar cell plants in the desert does not hold, because one could simply make electricity from it and use it with high efficiency (which is also done in Iceland, e.g. for aluminum production). So it is sheer waste of energy and in consequence massive entropy increase whie we still by far do not yet have enough renewable energy.

3.1.2. entropy estimation of final storage

For the entropy consideration, we first look at the entropy of the atmosphere, which contains about 0.06% (weight percent) CO_2. Since we based everything above on 1 ton of CO_2, this means that we have to look at a mixture of CO_2 with about 16.7 tons of other components of the air (nitrogen and oxygen and other components such as water, trace gases, etc) (all of which a DAC plant pulls through the filter systems, after all).

The entropy S of the air containing CO_2 is calculated approximately according to the formula for the mixing entropy (simplified for ideal gases and closed systems, which we have neither, but it is enough to assume these simplifications, see[16])

$$S = kN_1 \ln \frac{N_1 + N_2}{N_1} + kN_2 \ln \frac{N_1 + N_2}{N_2}$$

We have approximately 22,727 moles of CO_2 (= 1 ton) in the air mixed with about 380,000 moles of other air constituents, if they had the same molecular weight as CO_2. But the mixture of nitrogen and oxygen has lower molecular weight, so in 100 wt% air (which contains 1 ton of CO_2) we have about 380,000*1.5 = 570,000 moles of other air components.

1 mole contains about $2*10^{23}$ molecules (which is the definition of "mole"). We put these values into the above formula and get (with $k=1,3*10^{-23}$)
$2.76*22.727*\ln((N_{CO2}+N_{air})/N_{CO2}) + 2.76*570.000*\ln)(N_{CO2}+N_{air})/N_{air}) =$
2.76*22,727*3.26 + 2.76*570,000*0.039 = 265,843 J/K
Since we want to filter out 1 ton of CO_2 from the air that has this extremely high entropy value, we have to reduce the entropy of the atmosphere by 265,843 J/K, because if we get pure CO_2, outside of the atmosphere, its mixing entropy is zero. (The mixing entropy of the remaining other atmospheric components stays the same as before.)

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15 https://www.euractiv.com/section/energy/opinion/analysis-efficiency-of-coal-fired-power-stations-evolution-and-prospects/

16 http://wwwex.physik.uni-ulm.de/lehre/gk2-2007/node31.html

Any entropy decrease inside an open system (here: atmosphere) can only be achieved if a lot of energy is invested (we have already seen, how much is needed). The decrease of entropy (i.e.: the export of entropy) causes (because of the 2nd law of thermodynamics) an increase of entropy outside any DAC plant, and this in addition to the entropy increase related to the conversion and supply of the process energy.

This is not changed by the argument that this is regenerative energy conversion, which is intended to be used for DAC and CCS. As to the question whether we actually have an energy surplus from regenerative sources (wind and sun) that could allow us to use it wastefully, I have argued above: We don't have it.
- In addition, however, we should consider entropy: The statistical interpretation of entropy is well known; it states that in a system where entropy increases, disorder increases.

We cause twofold entropy increase, by exporting the mixture entropy out of the absorbed air (to the outside world) and by providing the process energy. So somewhere on earth disorder will increase, disorder is decrease of complexity. We notice this then where we extract the raw materials for the production of the equipment (with the help of which we provide the energy) and where we process them to the equipment: Silicon etc for solar cells with all the electrical, electronic and mechanical trappings, lithium mining for batteries, water (large amounts of process water for final storage), cement for wind power, power grids and so on. All requires land that is no longer available for biodiversity, degradation of biodiversity is an indicator of entropy increase, "entropy pollution".

Another aspects needs to be considered as well, the scale. Niall Mac Dowell et al. analyzed "the role of CO_2 capture and utilization in mitigating climate change" (title of their paper).[17] They showed by looking at the volume of CO_2 to be pressed into deep earth storages, that these would need to be 1,033 million barrels (MMbbl) of CO_2 per day, if only the global CO_2 daily production would need to be captured. The current global oil production is reported to be 87-91 MMbbl per day. Then they write: "This means that global CO_2 production today is approximately a factor of 10 greater than global oil production today, and, at current rates of growth, may be as much as a factor of 20 greater in 2050." This would mean, they continue saying, that until 2050, an industry "substantially larger than the global oil industry would have to be installed" [within from now on only 25 years] while the scale of the current global oil industry was built up within a whole century. (An analysis of energy demand of such technologies was not done by the authors.)

3.2. conversion of CO_2 into useful raw materials?

In an article in the German science magazine "Bild der Wissenschaft 'Spezial: Rohstoffe' (Sommer 2023)" with the title "Heute Übeltäter, morgen Held" (translated as "Today's evildoer, tomorrow's hero", p. 78 ff), Dr. Frank Frick presented a series of processes that are currently being researched or developed and tested at least on a laboratory scale or in some cases already on a pilot scale.

CO_2, which is very inert, is supposed to be a valuable raw material "soon"; the impression is given that all that is needed is a few technical optimizations and a few less cost-conscious customers, and CO_2 can be removed from the atmosphere and used en masse as a raw material. And then the economy would become "sustainable."

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17 Mac Dowell, N., et al, nature climate change, 7, (2017), 243–249, https://www.nature.com/articles/nclimate3231

(The drastically disadvantageous energy and entropy balance of removing CO_2 from the atmosphere was already shown in 3.1.)

The aspect of economy was mentioned, also as an example that Covestra had stopped polyol production with CO_2 as raw material, among other reasons, because of sustainability aspects, but, according to the author, only 'customers are needed who accept a surcharge in order to score in the field of sustainability'. No account was given of what arguments had led Covestra to discontinue the product 'for sustainability reasons'.

We will therefore now take a closer look at what those reasons might be. In doing so, we will not go into the individual reactions / processes described in the above-mentioned article, but rather take a very simple reaction as presented by Prof. Benjamin List (Nobel Prize winner "organic catalysis") in the ZEIT magazine of 11. 5. 2023 in the form of a question and some explanations. The magazine had asked 12 well-known scientists for the "big unsolved questions in their field to which they would like to get an answer". Prof. List asked, "Can we stop climate change by splitting carbon dioxide into its elements?" and then bury the carbon again as coal in the Ruhr region, for example, he said.

If we want to split CO_2 back into C and O_2, we have to expend at least the 393 kJ/mol of formation enthalpy that was released when C and O_2 reacted to form CO_2 in the combustion process. "At least" because the process of re-splitting also involves loss of efficiency (i.e., entropy generation). However, because of the typical efficiency of power plants, we got only about half of the enthalpy of formation, around 200 kJ/mol, of energy available when we produced CO_2!

Even catalysis (the specialty of Prof. List) cannot change this relationship, because a suitable catalyst cannot change the enthalpy of reaction, but can decrease the activation energy and increase the reaction rate, that’s it.

In addition to the aspect of the miserable energy balance, there is also the entropy aspect: This can be estimated by comparing the standard entropy values of the substances involved:
C: 6 J/K*mol, O_2: 205 J/K*mol; CO_2 214 J/K*mol[14]; i.e., we reduce the entropy from 214 to 211 J/K*mol (which, outside of this system, comes out as an entropy increase); this doesn't sound particularly dramatic, but it adds up to the entropy increase required from providing the energy to split CO_2 into C and O_2.
- And per ton of CO_2 these are already considerable amounts, namely almost 70,000 J/K, and we are not dealing with 1 ton of CO_2, but with billions and billions of tons.

If now - as presented in the article by Dr. Frick - CO_2 is to be converted with H_2, the energy requirement and the associated entropy increase of hydrogen production are to be added. It does not become more sustainable, but only more environmentally harmful, ecologically even more absurd. Because it is simply the case that CO_2 is an indicator for large entropy rise - and entropy can be lowered only if outside of the open system (in which we lower the entropy) the entropy rises excessively.

N. Thonemann performed a metastudy about the environmental aspects of CO_2-based chemical production[18] and came to the conclusion, that “that there is no CO_2-based chemical production technology that performs better in each IC [environment impact categories] than the conventional

18 https://www.sciencedirect.com/science/article/abs/pii/S0306261920301112

production alternative." This is not surprising when looking at entropy, because entropy is an indicator for negative environmental impacts.

A. Kätelhön et al. analyzed the "climate change mitigation potential of CCU in the chemical industry".[19] While Mac Dowell et al.[17] have shown, that the amount of raw material needs, even if it were theoretically possible to replace all organic raw materials of the chemical industry somehow by CO_2-based chemicals (generated via CCU), "it becomes clear how negligible the contribution of CCU will be to the global CO2 mitigation challenge", Kätelhön concludes in addition, how absurd such an approach would be: "Exploiting this potential, however, requires more than 18.1 PWh of low-carbon electricity, corresponding to 55% of the projected global electricity production in 2030." In other words: For (just only theoretically thought!) removing at best 10% of the global yearly CO2 emission, the chemical industry would need 55% of the worldwide renewable energy production (as projected for 2030). This is, again in other words, nothing else than the manifestation of entropy.

The 2nd law of thermodynamics, according to which entropy increases continuously, cannot be overridden on a global scale. Neither can can we get around the fact that if we want to reduce the entropy in a certain open system (like: atmosphere) or use materials with a high entropy content (like CO_2), we must invest a huge amount of energy leading to huge amounts of entropy on a global scale. The laws of nature can not be overcome by ignoring them.

4 Conclusions

But this is not taken into account at all in the public discussion, neither in the science field. The dilution entropy alone (which we have to export out of the treated air "into the environment" when separating the gases, i.e. separating the CO_2 from the other components of the air, because CO_2-poorer air contains less entropy) is enormous.[13] In addition, entropy is generated by providing the necessary energy. This may seem very theoretical to some, but it is not: impoverished ecosystems; landscapes hostile to life; farmland rendered basically dead by pesticides and insecticides with, if at all, only one centimeter of humus; waste heat; mountains of waste; polluted waters and seas; microplastic; decline of biodiversity (birds, insects!) and many more are signs of entropy "pollution". Neither in terms of energy, nor in terms of entropy is CO_2 disposal or use sustainable.

The climate and biodiversity problem can only be solved together, and this with the help of photosynthesis: in ecosystems as close to nature as possible, left (or renaturalised to) as wild as possible, with organic agriculture practiced worldwide.[20] Technology can help us with efficient industrial processes, but not with CO_2 capture and sequestration. Chemical conversion of CO_2 into useful materials should be left to plants, fungi and microbes.

So far, if sustainability was discussed with the attempt to approach quantitative criteria, this was limited to „1) Exergy balance 2) Ratio or fraction of renewables expressed as exergies 3) Structural costs in terms of exergy".[21] Entropy is not considered yet at all. However, this is unavoidable as also (e. g.) renewable energy is not available without having generated lots of entropy.

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19 https://www.pnas.org/doi/10.1073/pnas.1821029116

20 https://www.nature.com/articles/s41558-023-01631-6, https://www.pnas.org/doi/10.1073/pnas.2210561119

21 cf reference[1], p. 234; „exergy" is understood as „energy useful for doing work"

Ultimately, entropy alone could be seen as a key criterion for sustainability. All processes that humans operate, together with natural producers, should in total not generate more entropy than the earth can radiate (which is about 230 W/m² of the earth's surface[22]). We are far away from this, which means: We are generating much more entropy than the earth can radiate off; therefore, in consequence entropy is accumulated on earth – where else could it be? So we can only approach a much more sustainable level of living and managing our economy, agriculture and ecosystems, if we begin to introduce entropy generation analysis for our industrial products and processes, including agricultural procedures, including climate change mitigation and biodiversity crisis resolution.

Abbreviations

DAC

CCS

CCU

IC

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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22 Ebeling, W., Feistel, R., "Self-Organization in Nature and Society," conference "The Human World: Uncertainty as a Challenge," Frolov Lectures 2017, accessed here: https://www.researchgate.net/publication/316878591_Selbstorganisation_in_Natur_und_Gesellschaft_und_Strategien_zur_Gestaltung_der_Zukunft, see also Feistel, R., Ebeling, W., "Physics of Self-Organization and Evolution," Wiley-VCH 2011, pp. 97/98.