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Thermodynamic analysis of CO_2 removal and storage

Entropy as a criterion for sustainability

BERNHARD WESSLING

This large-scale pilot plant for carbon capture went into operation in 2020 in the Japanese city of Mikawa at the local biomass power plant. The power plant is fired with palm kernel shells as its primary fuel and has a capacity of 50 MW *(photo: Toshiba ESS).*

Thermodynamics plays virtually no role in the climate debate, especially entropy. This is a mistake, because analysis using non-equilibrium thermodynamics shows that all the technological processes discussed for capturing CO_2 *from the air or industrial emissions and storing it are fundamentally unsustainable.*

I

Four aspects can be observed in the climate debate. First, the debate on global warming often overshadows the dramatic crisis in biodiversity, even though the two are linked. Second, the term "sustainability" has been used increasingly inflationarily and, at the same time, emptily for years. Thirdly, in popular science articles, especially when it comes to CO$_{(2)}$-saving or CO(2)-removing technologies, thermodynamics plays an extremely rare role [1], even though the climate results from global energy conversion, which is at the core of thermodynamics. Fourthly, when thermodynamics is mentioned, it is in the context of conventional equilibrium (EE) thermodynamics; entropy is understood according to the second law of thermodynamics
entropy is understood as "always increasing."

At most, in connection with the physics of life processes, Erwin Schrödinger is mentioned [2] as saying that life arose because organisms "feed" on negative entropy. He writes that organisms only remain alive by constantly extracting "negative entropy" from their environment. However, this is not defined thermodynamically and is merely a mathematically inspired neologism. GG thermodynamics cannot explain how systems arise that are more complex than what we would expect over time due to the increase in entropy. These include plants, animals, ecosystems—phenomena that create life—but also inanimate complex structures such as galaxies, river deltas, or mountains.

Non-equilibrium thermodynamics However, Schrödinger also said something else very important: life requires "previously unknown other laws of physics." Ilya Prigogine established such new laws with his non-equilibrium (NGG) thermodynamics and was awarded the Nobel Prize in Chemistry in 1977 [3]. Even today, these laws are not taught as part of basic thermodynamics courses at universities, but only in specialized seminars and online courses.

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in some departments of physics and engineering. The key finding: when an open system receives a *supercritical amount of energy*, it cannot dissipate this energy input other than by *exporting entropy* beyond its boundaries into its environment. In the process, complex *dissipative structures* form within the system.

Among other things, Prigogine investigated a very complex system: the oscillating Belousov-Zhabotinski reaction is also known in physics as an example of chaotic systems. If this reaction is allowed to take place in a thin layer of liquid in a Petri dish, striking alternating patterns emerge (Figure 1) that are similar but never identical. In general, complex structures arise due to many internal nonlinear interactions interactions between processes that are inherently nonlinear. Such systems are *far from equilibrium* and are therefore not *equilibrium-based* , such as those studied by Ludwig Boltzmann.

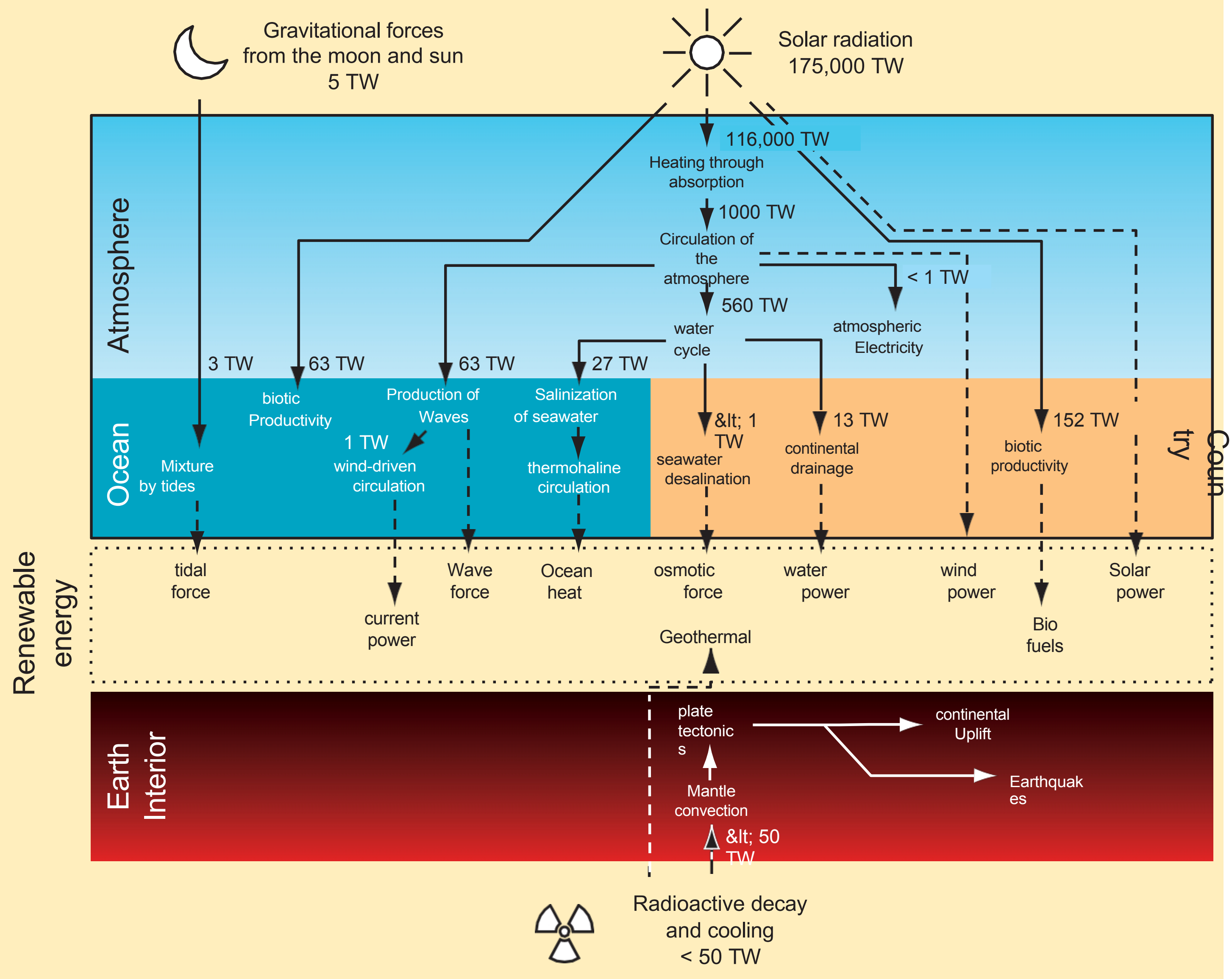
Fig. 1 ***The Belousov-Zhabotinski reaction oscillates – which is visually apparent thanks to suitable indicators – between different states. When executed in a flat shell, this repeatedly creates new dynamic patterns. The reaction mechanism is relatively complicated. In three different reaction groups, there are a total of 18 partial reactions, the theoretical treatment of which requires coupled differential equations. The energy supplied comes from the chemical potential contained in the reaction partners. Entropy export occurs through the production of CO$_2$, which leaves the reaction space, accompanied by the formation of complex dynamic structures. Images and videos of the reaction: https://t1p.de/BelZhab.*** *(Courtesy of Approved by S. Morris, University of Toronto, Canada, and M. Rogers.*

The Earth system itself is a significant example of this. It receives a "supercritical" energy input in the form of radiation from the sun, plus residual heat from the early days of the planet and a heat flow from radioactive decay within the Earth (Figure 2). In Prigogine's terminology of NGG thermodynamics, "supercritical" means that a system is far from equilibrium above a critical value. Plate tectonics and mantle convection create complex landscapes and oceans in which the sun, with its supercritical energy input, has allowed plants and animals to evolve, forming living dissipative structures. These highly complex structures and processes result from NGG. They are accompanied by entropy export into space. In Prigogine's view, there is no undefined "negative entropy." Entropy export is consistent with the second law of thermodynamics, because entropy increases constantly in relation to the entire universe, but in the open system of Earth it decreases as long as the supercritical solar energy import remains and the dissipative structures are not destroyed.

At this point, I would like to provide some background information on my academic career. I had never heard of this new thermodynamics during my chemistry studies, and when I received my doctorate in 1977, I was not even aware that Prigogine had been awarded the Nobel Prize in Chemistry, nor did I know what he had been awarded it for. In the course of my polymer chemistry and physics research in a medium-sized company, I then came across phenomena that I could not explain with my GG thermodynamic understanding. In dispersions—colloidal systems—the scientific literature according to the finely dispersed particles should be statistically evenly distributed. However, I found highly complex structures (Figure 3). After many detours, I came across Prigogine's work. I realized that, as an organic chemist, there was no popular science introduction to NGG thermodynamics to help me get started, so I have since attempted to fill this gap with my own book [4].

After getting into Prigogine's NGG thermodynamics, I came up with a special NGG theory for colloidal systems [/], which describes the surprisingly complex structures and processes that lead to their formation. I talked about this with two world-leading NGG thermodynamicists, who reviewed it: Grégoire Nicolis, Prigogine's co-author and his successor in Brussels, and Werner Ebeling, a researcher at Humboldt University in Berlin who worked closely with both of them. This theory forms the basis of an innovative nanotechnology I developed for the polymer chemical production and subsequent dispersion of electrically conductive polymers. We were able to successfully launch this technology on the global market with the company of which I was managing partner [6, 7]. It is therefore anything but a purely abstract theory far removed from technical application. As this will become important later on, I have included this digression into my work as an industrial researcher.

FIG. 2 | EARTH AND RENEWABLE ENERGY



Estimation of planetary generation and transmission rates of free energy and their relation to various forms of renewable energy. Figures are given in terawatts (1 TW = 1= ^{1012} W) [1].

Entropy explained simply

Entropy is usually misunderstood as a measure of disorder in a system that is constantly increasing. A more accurate definition is that entropy is a measure of the usability of energy. Matter contains chemical energy; entropy therefore also indicates the usability of substances, which means that substances with a high entropy content are of little or no use. If we take Boltzmann's statistical interpretation of entropy – from which, figuratively speaking, entropy is derived as a "measure of disorder"—our understanding expands: the more probable a state is, the higher its entropy content. This applies to disordered systems such as the distribution of gas molecules in a volume, which Boltzmann investigated, but also for highly ordered crystals. In crystals, it is possible to predict with a very high degree of certainty which chemical element will be found at which location; the entropy is therefore not as high as in a gas-filled balloon, but much higher than in a living cell. This is because the chemical elements occupy positions and the molecules formed from them take on structures for which the probability is close to zero, meaning that the entropy is extremely low.

If we were to copy a photo of a leafless oak tree with its branches many times over to create a monoculture of identical oak trees, this would be the image of an artificial forest with comparatively high entropy. However, the real forest would be made up of oak trees which, even if they were twin oaks or even clones, would all form a complex, never identical network of branches, even if they were the same age and had the same growth background (Figure 4). It is at a much lower level of entropy than the model monoculture. The same applies to snowflakes, which form similar patterns but are never 1:1 copies of a master snowflake. In Prigogine's sense, oak trees, snowflakes, organisms, ecosystems, river deltas, even a national economy, the infrastructure of our country, and international interdependencies are dissipative structures.

These are all examples of NGG systems or processes that are far from equilibrium due to a supercritical energy input and export entropy (Figure /b). Only when this energy input dries up do they develop in accordance with the

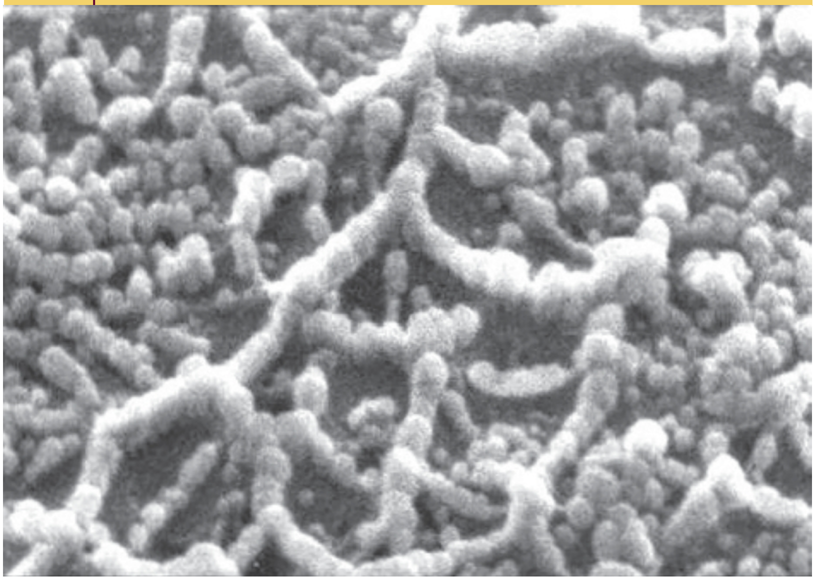
2. Main principle toward equilibrium: Energy decreases, entropy increases (Figure /a); processes slow down, structures decay. Leaves fall from trees in autumn and decompose, but in spring the process of building complexity begins again, including in the soil, where microorganisms recycle the fallen leaves. Organisms that no longer consume food become sick and die. Infrastructure decays without constant maintenance, and the economy of a country whose energy supply is weakening shrinks.

Entropy is therefore primarily an inversely proportional measure of the complexity of a system: the more complex the processes and structures, the lower the entropy content. Or, in other words, an increase in entropy is a sign of a loss of complexity and functionality in processes. Entropy is constantly exported from open dynamic systems into which supercritical amounts of energy are imported, in the form of substances or, in living systems, as food, ultimately ending up in the universe. The internal processes behave nonlinearly and interact with each other in a nonlinear manner. NGG is what keeps us alive; equilibrium embodies the opposite. The Austrian-American theoretical biologist and systems theorist Karl Ludwig von Bertalanffy [8] wrote about this: "Biologically speaking, life is not the maintenance or restoration of equilibrium, but essentially the maintenance of imbalances, as the doctrine of the organism as an open system shows. Achieving equilibrium means death and consequent decay."

The question now arises as to whether this finding is relevant to our topic, the removal of $CO_2$from the air and geological storage, or in short Final storage, relevant to practice. The answer is yes, and much more so than is generally assumed. Basically, Prigogine's NGG thermodynamics is another pillar for understanding our world, on a par with the theory of relativity, quantum physics, and the theory of evolution. This leads us to real-life applications. More specifically, we want to use NGG thermodynamics to investigate processes that reduce, avoid, or reverse CO($_2$)emissions. The former processes capture CO($_2$)directly at the source of emission using filter systems or solvents and fall under the familiar umbrella term of *carbon capture and storage (*CCS) [9]. The latter processes, which remove CO($_2$)directly from the atmosphere using filter systems, are referred to as *Direct Air Capture (*DAC). In both processes, the CO($_2$)is then to be stored permanently. Either it is injected directly into deep layers of the earth next to the filter system or, after liquefaction, it must be transported to a final storage site [10]. it can also be chemically bound, for example in CaCO($_3$), and then stored permanently. Alternatively, the CO($_2$)could also be chemically converted and used; these processes fall under the term *Carbon Capture and Use (*CCU) [12].

All three processes require enormous amounts of energy. Nevertheless, they are classified as sustainable with the proviso that renewable energy sources would be used. Apart from the energy issue, it is important to understand that we cannot harvest CO_2without incurring entropy costs.

FIG. 3 | COMPLEX STRUCTURES IN DISPERSIONS



According to scientific literature, dispersed particles should be statistically evenly distributed in the matrix. Instead, the author discovered that they are concentrated in layers and form complex network filaments. Filaments from soot particles dispersed in polystyrene are shown here as an example.

Fig. 4 ***No oak crown looks exactly like another oak crown*** *(courtesy of K.-H. Limmer)****.***

Solar and wind energy, as well as electrolytically produced hydrogen, require raw materials, space, and water, which means that this energy conversion also generates a significant amount of entropy. We will now take a closer look at how much this is for DAC processes.

Energy requirements for CO_2 storage

To this end, we compare the enthalpy of formation of CO_2 with the energy required by DAC to capture the gas and store it in deeper layers of the earth as $CaCO_3$: 1 t CO_2 contains 22,722 mol CO_2, which corresponds to an enthalpy of formation of −8.9· ^{106} kJ [13]. Of this, we were able to use less than a third, or about 2.5/· 106 kJ, as electrical energy in the previous combustion process in a typical coal-fired power plant. The rest ended up as waste heat and ash, i.e., as entropy, in the environment.

Table 1 provides a technical and economic overview of systems for direct air capture [10]. The total heat requirement for DAC ranges from 1420 to 22/0 kWh_{th}per ton of $CO_{2,\text{depending}}$ on the degree of heat integration. The required electrical power is specified as 366 to 764 kWh_{el}per ton of CO_2 . This results in an average of 2000 kWh_{th} and 600 kWh_{el} .
The heat required is therefore converted to
7.2· ^{106} kJ/t CO_2 – not much less than the enthalpy of formation. However, it is not produced with 100% efficiency.
efficiency; at an efficiency of 80%, 9· ^{106} kJ of primary energy is required, which corresponds almost exactly to the enthalpy of formation. The electricity required is equivalent to 2.16· 106 kJ; with a global average efficiency of 31% for coal-fired power plants [14], this means that 7· 106 kJ of primary energy is consumed, with wind and solar power plants having similarly low efficiency levels.

This means that a total of 16,· ,^{106} kJ is required to remove 1 ton of $CO_2$from the atmosphere. That is almost twice as much as the CO_2formation enthalpy during combustion! Consequently, the energy requirement for DAC is about six times higher than the electrical energy we were able to use to generate this 1 ton of $CO(_{2)}$! In 2024, global $CO(_{2)}$emissions were 37.41 Gt [1/]. This means that we need 22 PWh(el) and 7 PWh(th) (rounded to the current level) just to stabilize the CO_2 concentration at current levels, we will need approximately 22 PWh_{el} and 7/ PWh_{th} , respectively. Two-thirds of the total electricity generation forecast for humanity in 2030, approximately 33 PWh, would therefore be required for DAC. It should be noted that this includes all energy sources, not just renewable energy sources.

According to this estimate, only 9 PWh_{el} of conventionally or renewably generated electricity would remain for free use in industry, infrastructure, mobility, and private households. However, the total global demand for electrical energy in 2024 was around 30 PWh_{el} [16], which means that only just under a third of this would then be available for actual consumption. This shows that the argument that DAC and CCS would be powered by renewable energy in the future, for example from large solar power plants in the Earth's sun belt, is nonsensical, as this would require an absurdly large expansion of renewable capacities. It is much smarter to use green electricity directly. Above all, such a scenario would also lead to a massive increase in the entropy exported into the environment, which we will discuss in the next section.

Entropy balance of CO_2 storage

To estimate entropy, we consider the entropy of the atmosphere, which contains approximately 0.06 percent by weight of CO_2. Since we are calculating per ton $_{\text{of } CO_2}$, this means that we are dealing with a mixture of 1 ton $_{\text{of } CO_2}$and approximately 1,670 tons of other components of air—nitrogen, oxygen, and other components such as water, trace gases, etc.—which a DAC plant pulls through its filter systems.

The entropy S of the CO_2-containing air is calculated approximately using the formula for mixture entropy – simplified for ideal gases and closed systems [17], where N denotes the number of molecules:

$$S = k_B N_1 ln \frac{N_1 + N_2}{N_1} + k_B N_2 ln \frac{N_1 + N_2}{N_2}.$$

1 t with 22,727 mol CO_2 (N_1) is diluted in approximately /7,· ,^{106} mol nitrogen, oxygen, etc. (N_2). 1 mol contains approximately 6,· ,^{1023} molecules. We insert these values into the above formula and, using the Boltzmann constant $k_B = 1.38·$ $^{10-23}$ J/K, we obtain an entropy value of approximately 1.47 MJ/K. To this must be added a further entropy value from the mixture entropy of H_2 O in air: This is because the filters that extract CO_2 also filter

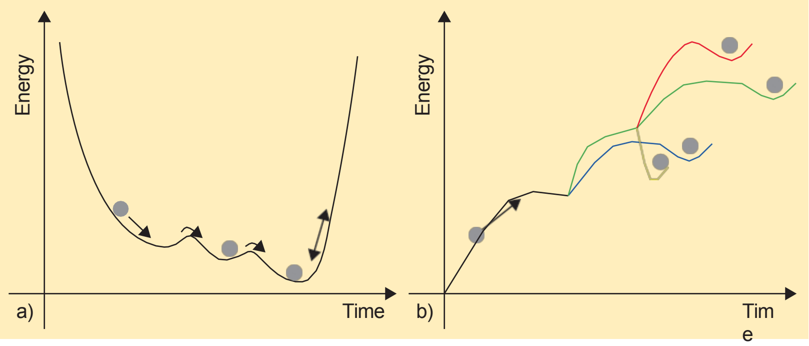
two to five molecules of water per molecule of CO_2 from the air. If we only take the lower value of two molecules of H_2 O per molecule of CO_2, this results in approximately 2.68 MJ/K, giving us a total entropy of 4.1 MJ/K. Since we want to filter 1 ton $_{\text{of }CO_2}$from 1,671 tons of air, which has this extremely high entropy value, with our DAC system, we have *to reduce* the entropy of the intake air by 4.1 MJ/K. This is because when we obtain pure $_{CO_2}$outside the atmosphere, its mixture entropy is zero.

According to NGG thermodynamics, entropy reduction in an open system, in this case filtered air, can only be achieved if a supercritical amount of energy is invested—in fact, in the previous section, we determined 16,· ,^{106} kJ of primary energy per t $CO_2$for this. The export of entropy from the air causes it to increase outside of any DAC plant somewhere on the Earth's surface, in addition to the increase in entropy associated with the conversion and provision of the process energy. The argument that this is renewable energy conversion intended for use in DAC does not change this: This also generates massive entropy, apart from the fact that we already have far too little of it without DAC. An estimate shows that the amount of entropy generated by DAC is orders of magnitude higher than the entropy reduction in the filtered air: As we estimated in the last section, it is two-thirds of the primary energy used.

In a system in which entropy increases, complexity decreases. With DAC, we are causing a multiple increase in entropy globally by exporting the entropy of the mixture from the absorbed air and by providing process energy. So, as entropy increases somewhere on Earth, complexity will decrease: where we extract the raw materials for the production of the process plants and where we process them into machines: silicon for solar cells with all their electrical, electronic, and mechanical microstructures, lithium mining for batteries, water—large quantities of industrial water for final storage—copper, plastics, steel, cement for wind power, power grids, DAC filters, and where we provide the process energy. All of this requires land that is no longer available for biodiversity, i.e., complexity. The deterioration of biodiversity is an indicator of increasing entropy, which is synonymous with damage to the environment.

We must also take into account the technical magnitudes involved. Niall Mac Dowell of the Centre for Environmental Policy at Imperial College London and his co-authors analyzed „the role of CO_2capture and utilization in mitigating global warming" in *Nature Climate Change* in 2017.

FIG. 5 | ENERGY INPUT AND ENTROPY EXPORT



Energy curve over time: The energy input is inversely proportional to the entropy export; the entropy curve is not shown here. a) In equilibrium, energy tends toward a minimum and entropy toward a maximum. b) In non-equilibrium (NGG), the energy content increases, while entropy decreases inversely proportional to this. In NGG, the real curves branch off into different dissipative structures. These form local energy minima with complex structures that are similar but not identical.

Climate change [18]. Based on the volume of $_{CO_2}$that would have to be compressed into deep underground storage facilities, they showed that this would amount to 1,033 million barrels $_{\text{of}}$ $_{CO_2}$per day *if only the global daily$_{CO_2}$production were to be captured*. Global oil production is estimated at 87 to 91 million barrels per day. They conclude: "This means that global CO$_{(2)}$production [in terms of volume] is currently about 10 times greater than global oil production and, at current growth rates, could be as much as 20 times greater by 20/0." This would mean, they continue, that by 20/0, an industry would have to be built up "that is significantly larger than the global oil industry" in order to achieve the targets agreed at the Paris Climate Conference while maintaining the same energy mix. It took about a century to build up today's global oil industry!

Even if it were possible to build up such a gigantic industry in a very short time, where would the raw materials come from, and where would these huge factories be located? Where would the $_{CO_2}$be captured and stored, and how many additional liquefaction plants would have to be built to transport the CO_2 emitted in Germany alone and removed from the atmosphere to Norway and Denmark?$_2$emitted in Germany and removed from the atmosphere to Norway and Denmark? The Leopoldina called for around 100 million tons of $CO_2$to be captured annually in Germany [20]. This would require a gigantic amount of energy. And the result would only be a stabilization of the CO_2concentration in the atmosphere, not a reduction.

The enormous increase in entropy production that we have estimated here underscores that the collateral damage to the environment caused by DAC processes will be many times greater than the hoped-for positive effect on the climate. Biodiversity would decline even more dramatically.

Conversion of CO_2 into useful raw materials?

Finally, we turn to the idea of chemically converting CO_2 into raw materials as currently used in industry on a significant scale. This vision of using CO_2 as a valuable raw material falls under the CCU processes briefly introduced above. The drastically unfavorable energy and entropy balance involved in removing $_{CO_2}$from the atmosphere, which is a prerequisite for subsequent chemical processes, alone makes such a promise of a sustainable material cycle implausible. Since $CO(_{2)}$is very unreactive, further chemical conversion cannot contribute to improving the negative sustainability balance—on the contrary.

Benjamin List, who was awarded the Nobel Prize in Chemistry in 2021, asked this question in the 11/2023 issue of ZEIT magazine: "Can we stop climate change by splitting $_{CO_2}$into its components and storing C back in old mines?" The answer: To do so, we would have to expend *at least* the 393 kJ/mol of enthalpy released during the reaction of C and $O(_{2)}$ to form $CO(_{2)}$ in the combustion process. And only a third of that was usable due to the typical efficiency of power plants!

In addition to the miserable energy balance, there is also the aspect of entropy. This can be estimated by comparing the standard entropy values of the substances involved: For C, it is 6 J/K· mol, for O_2 20/ J/K· mol, and for CO_2 214 J/K· mol. This means that we reduce the entropy from 214 to 211 J/K· mol, which appears as an increase in entropy outside this system. Per ton of CO_2 ,this is already considerable, namely almost 70,000 J/K, and we are dealing with billions of tons of CO_2.

If $CO_2$is to be reduced using H_2, the energy requirement, efficiency, and associated increase in entropy from H_2O electrolysis must be added$_{to}$ the energy requirement for supplying the CO_2. Hydrogen is not free, either in terms of energy or entropy: To produce 1 ton of hydrogen, 40,000 to 80,000 kWh$(_{el)}$are required $_{[}$ 20]. Globally, wind power is mostly found [20] where water of drinking quality is rather scarce, which is necessary for the electrolysis of water. If only seawater is available, its desalination not only requires additional electrical energy, but also causes massive damage to the marine ecosystem. Desalination produces toxic brine, which is additionally contaminated by the chemicals required in the process: nothing but entropy!

In addition, the production of "green" hydrogen using renewable energy sources is not yet viable in the balance sheet of the Entropy costs are significantly higher than if the renewable electricity were used directly, for example for electric mobility. Particularly unfavorable is the conversion chain from water to hydrogen and then its use for the conversion of $_{CO_2}$into e-fuels, which are then intended to power cars with combustion engines. The energy required to produce e-fuels is about a factor of 10 greater than if the renewable electricity were used directly in electric cars [20]. The same applies to any chemical produced from $_{CO_2}$using "green" hydrogen.

Not surprisingly, Arne Kätelhön from the Institute for Technical Thermodynamics at RWTH Aachen University and his co-authors in [21] come to the absurd-sounding conclusion that a complete supply of organic raw materials for the global chemical industry based on CO_2: "However, exploiting this potential requires more than 18.1 PWh of low-carbon electricity, which corresponds to // % of the global electricity generation forecast for 2030." In other words, in order to eliminate – theoretically – at best 10% of global annual $CO(_{2)}$emissions, such a $CO(_{2)}$-based chemical industry alone would require //% of the total *global* electricity generated from renewable energy sources in 2023, amounting to 29 /00 TWh [22]. This, in turn, is nothing more than a manifestation of entropy.

If we want to reduce entropy in a specific open system, in this case the atmosphere, or use materials with a high entropy content such as $CO_2$and thus reduce entropy, we have to invest an enormous amount of energy. This leads to a multiple increase in entropy on a global scale. The laws of nature cannot be overcome by ignoring them. The alternative to DAC and CCU is $_{CO_2}$storage in natural ecosystems, whose entropy production is directly radiated away from the Earth [11]. If we just let nature do its thing, its storage capacity would be way higher than our current $_{CO_2}$emissions (additional material and [12]).

Summary

Non-equilibrium (NGG) thermodynamics and the interpretation of entropy based on it are only taught at universities in special courses. The resulting lack of scientific understanding among the general public has a particular impact on the climate debate. NGG thermodynamics should therefore become a core science in this field. Among other things, the article uses NGG thermodynamics to show that filtering $_{CO_2}$from the atmosphere (direct air capture, DAC) and using it as a raw material (carbon capture and use, CCU) would, given the goal of

On the topic

***What a coincidence**. On the origin of unpredictability, complexity, crises, and time, Bernhard Weßling, 2nd edition, 364 pages, Springer Vieweg, Wiesbaden 2025. Softcover/eBook \$29.99/\$24.99€ , ISBN-13: 978-3- 658-46426-4/… -46427-1.*

Stabilizing the climate requires absurdly large amounts of energy. In addition, the technical equipment required for this must export enormous amounts of entropy into the environment. DAC and CCU are therefore drastically unsustainable. This means that the desired positive effects for the climate cause much more massive collateral damage to the environment, for example in terms of biodiversity. Instead of DAC and CCU, natural ecosystems can and must contribute to increased $CO(_2)$storage.

Keywords

Climate, thermodynamics, non-equilibrium thermodynamics, entropy, sustainability, CO_2storage, direct air capture, DAC, carbon capture and use, CCU.

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Additional material

The additional text "Entropy as a key criterion for sustainability" can be found under "Supporting Information" at https://onlinelibrary.wiley.com/doi/10.1002/piuz.202/01731/suppinfo.

The authors

Bernhard Weßling received his doctorate in 1977 and went on to conduct research in polymer chemistry, colloid science, and thermodynamics, while also working as a chemical entrepreneur. He developed a new, non-equilibrium thermodynamic theory for colloidal systems and the world's first organic metal. It has since been used on a large scale in industry.
He is active in nature conservation and species protection and, alongside his career, is an investor and co-managing director of an organic farm. Sustainability also played a central role in his company. He has been working as a non-fiction author since 2020; see www.bernhard-wessling.com.

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Entropy as a criterion for sustainability

BERNHARD WESSLING

WILEY-VCH

Entropy as a key criterion for sustainability

BERNHARD WESSLING

Supplement to the article "Entropy as a criterion for sustainability," Physics in Our Time 2025.

Moors are not only highly efficient natural sinks for $_{CO2}$, but also entropy *(photo: B. Weßling)****.***

Some may think that the facts presented in the article are purely theoretical considerations and that "entropy" is, at best, interesting for academic discussion. This must be strongly refuted. Fundamentally, the Prigoginean non-equilibrium thermodynamics introduced in the article is a pillar of natural science on a par with the theory of relativity, quantum physics, and the theory of evolution. We need all these theories (and a few more) for a comprehensive understanding of our world.

This applies in particular to the consequences of the various processes discussed in the article, which fall under the umbrella term CO2 capture and storage. Not only do these require enormous amounts of energy, on the scale of humanity's entire primary energy production today, if we wanted to reverse our CO2 emissions from established combustion processes in this way. Above all, the entropy analysis presented in the article shows that these processes cause an enormous increase in entropy in the environment. To consider these consequences, we must look far beyond purely physical estimates. They are particularly evident in the living world. Impoverished ecosystems, hostile landscapes, fields sprayed to death with pesticides and containing less than a centimeter of humus, waste heat, mountains of trash, polluted rivers and oceans, declining biodiversity, and much more—these are all indicators of increasing entropy. One of the best-known examples is the decline in insect populations, which in turn causes a decline in the numbers and distribution of various bird species that feed their young on insects. Neither in terms of energy nor entropy is CO2 storage or utilization sustainable.

The climate and biodiversity problems can only be solved together. Photosynthesis in ecosystems that are as natural and wild as possible, wetlands, moors, and organic farming practices worldwide are particularly effective and far superior to all technical methods of CO2 capture. Technology can help us with efficient industrial processes, but not with CO2 storage. A comprehensive, detailed, and well-documented analysis of natural potential can be found in Chapter 8 of the book [1].

We learn from this consideration that entropy must be regarded as a key criterion for sustainability. All processes carried out by humans, together with natural sources, should not generate more entropy than the Earth can radiate as a whole – that is about 230 W/m² of the Earth's surface [2, 3]. We are a long way from that.

Literature

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