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Entropy, economics and sustainability: some conceptual clarification and many questions

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Abstract

This paper clarifies physical notions such as entropy and the second principle of thermodynamics and their relevance for analysing the economic system and sustainability. It also provides a structured overview of some relevant sustainability issues. It is an exploratory work intended to be useful as a starting point for further research. From the clarification of basic concepts and the review of relevant issues and dilemmas, one main idea emerges: the interrelationship between energy, materials and waste is inherent in the nature of the economic system as an entropic system that organises the satisfaction of human needs. However, this interrelationship is not always taken into account in sustainability analyses, which may limit the scope and usefulness of the conclusions drawn and the recommendations derived from them.

Cover image: Equisetum arvense initiating colonisation of a volcanic area with almost no vegetation in Iceland (photo taken by Pablo Aguirre Carmona).

Introduction

This paper deals with the concept of entropy and its relation to economics, specifically to the field of sustainability. It is not the conclusion of a paper but rather a guide to undertake it in an oriented way, clarifying basic concepts and structuring a set of relevant questions to build what could be called a "preliminary map of ignorance" of the writer of this text in the field of sustainability— starting point, much more than a point of arrival. After this introduction, the text is divided into five sections. The second section explains, from a physical point of view, the concept of entropy and other relevant related issues. The third section justifies the usefulness of the previous concepts for analysing the economic system. The fourth section is devoted to delimiting the scope of the study of sustainability. The fifth section then offers a structured list of relevant questions on economics and sustainability, with a suggested bibliography, without any pretension of exhaustiveness. The sixth and final section provides some concluding thoughts on the topic addressed.

Entropy and related issues[1]

Mechanical work and irreversibility

It is helpful to become familiar with two physical concepts before addressing the question of entropy: "mechanical work" and "irreversibility". The historical figure who linked them together, laying the foundations for the later definition of entropy, was Sadi Carnot, a French engineer and son of Lazare Carnot, a revolutionary and personal friend of Robespierre. Sadi Carnot wrote in 1824 the Reflections on the motive power of fire (Rovelli 2018, ch. 2), where he tried to analyse the maximum output that could be extracted from an engine.

Combustion engines use heat energy from a burning source (e.g. coal) to transform it into "mechanical work", like the steam engines that Carnot was interested in. This quantity measures something like the effect of a force and is defined as the product of that force and the displacement produced in the direction in which it acts. For example, when we push a piece of furniture to move it in our house, we apply a horizontal force parallel to the floor. If we manage to move the furniture, we will have done mechanical work equal to the force applied multiplied by the displacement produced.[2]

Doing mechanical work requires an expense of energy. Whoever receives the effect of the "work done" (whoever receives the force causing that work) increases his power somehow. It may gain speed, increasing its kinetic energy and altitude concerning the Earth's surface, which confers potential energy, or its temperature, indicating that it has gained internal energy. Work" is also produced when we circulate an electric current in a circuit because there are charges subjected to forces that move due to these forces.

Studying the steam engine's efficiency (how much mechanical work could be obtained from it), Carnot detected the critical phenomenon that interests us: heat passes from hot to cold, never the other way round. It is not like a falling ball but could bounce back up again. The heat never "bounces". When something freshly cooked is removed from the fire, it cools in contact with the air, never the other way around. The heat never concentrates on the food again, heating it spontaneously and cooling the air around it. It simply does not happen.

Heat transfer from a hot body to a cold body is an example of an irreversible process (Zemansky 1973, ch. 8,9). We can understand irreversible processes, in general, as those in which dissipative effects occur, which are those that prevent the work done by the system during the process from being returned to it in its entirety when it goes through the process in the opposite direction. Dissipative means that part of the work invested by the system is "lost" along the way; it becomes irrecoverable. It is lost because it has been transformed into heat, which is dispersed to the cooler environment,

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[1] This is based mainly on the following sources (Zemansky 1973, ch. 8, 9, 10; Feynman 1963, ch. 46; Pathria 1996; Tipler 1994, ch. 17; Rovelli 2018, ch. 2; Brodianski 1990, ch. 3,4).

[2] A curiosity. Some "mechanical work" is only produced when the force applied causes a displacement, which must also take place in the direction in which the force operates. Thus, when we lift the shopping bags from the ground so that they are hanging from our hands, we apply a vertical force that performs "mechanical work" because the bags are also displaced vertically due to our force. But our force only works by holding the bags hanging from our hands. No doubt, the muscles in our arms and hands will tire as we hold the bags at a constant height above the ground because those muscles must maintain sufficient tension to balance the force of gravity that would cause the bags to fall to the ground if we were not holding them. But there will be no more "mechanical work" done by the vertical force as long as it does not cause additional vertical displacement of the bags. And the vertical force also does not do any mechanical work if we move the bags from the supermarket to our house by walking along a horizontal street and keeping the bags at a constant height above the ground, hanging from our hands. In the latter case, the bag is displaced in the horizontal direction. Still, there is no vertical displacement, which is the direction of the force with which we hold the bags, so this force does not do any mechanical work because it is not responsible for the displacement.

dissipated, and cannot be taken back from there. So "irreversible" means that there is "dissipation", i.e. heat flow "from the hottest to the coldest", and this energy is dispersed into the surroundings so that it becomes unrecoverable energy.

In contrast, a reversible process takes place in such a way that, at the end of the process, both the system and the immediate external environment can be returned to their initial states without causing any change in the rest of the universe. If work has been done in the reversible process, the energy that it "cost" to do the work can be recovered in its entirety again by carrying out the reverse process.

Reversible processes do not exist in reality, but all real processes are irreversible because there are always dissipative phenomena that involve some flow of heat into the environment and some energy that is dissipated and becomes irrecoverable.

Reversible processes do not exist in reality, but all real processes are irreversible because there are always dissipative phenomena that involve some flow of heat into the environment and some energy that is dissipated and becomes irrecoverable. What differentiates them from each other is their degree of irreversibility. There are a multitude of everyday phenomena that correspond to highly irreversible processes. The conduction of heat from a system to its cooler external medium, which Carnot detected, is an example of thermal irreversibility (like the cooling of cooked food we have already discussed). When we stir a liquid (stirring coffee), stop a liquid that is rotating, or circulate an electric current through a resistance (as, for example, occurs in a hair dryer or a toaster), a source of energy (muscular in the case of liquids, electrical in the last example) has been used to do work that is transformed into heat, which will be dispersed in the environment and cannot be recovered later to be the source of new work. For its part, chemical irreversibility is present in any chemical reaction (reactions that occur in one direction do not occur spontaneously in the opposite direction), in the mixing of two substances, or the dissolution of a solid in water (salt dissolved in water does not spontaneously precipitate again to form a solid). These are all irreversible processes that only happen spontaneously in one direction, not the other.

The analysis of the "irreversibility" of the processes that take place in reality (and its contrast with reversibility, only theoretically possible but very useful as an element of comparison) is the territory of thermodynamics: that part of physics that analyses systems from a macroscopic point of view, analysing their states of equilibrium (those in which the measurable properties that characterise them are constant over time) and with particular attention to what has to do with the energy of the systems and the heat that they exchange with the exterior.

"The second principle of thermodynamics as loss of usable energy"

The first principle of thermodynamics is that of the conservation of energy: energy is neither created nor destroyed; it simply changes form, and it is constantly being transformed. This transformation is possible because there are different forms of energy (Zemansky 1973, ch. 9). Some provide mechanical work very easily, and others are not suitable for extracting mechanical work from them, such as heat flowing from hot to cold.

The second principle or law of thermodynamics states that whenever an irreversible process takes place (remember that all real processes are, to a greater or lesser extent, irreversible), the effect on the universe is equal to that which would be produced if a certain amount of energy were converted from a form in which it is completely usable for the production of work into a form which is totally unsuitable for conversion into work (Zemansky 1973, ch. 9).

Thus, if the first principle of thermodynamics states that energy is not lost but only transformed, the second principle states that this transformation always has the same direction: making energy less and less usable for obtaining mechanical work from it. It can be said that "energy goes from bad to worse".

Another equivalent way of stating the second principle of thermodynamics is to affirm that any irreversible process implies that the mechanical work that a system provides from the energy it possesses can be wholly transformed into heat. Still, from this heat, it is impossible to regain the mechanical work or internal energy that generated it (Tipler 1994, ch. 17).

An example is what happens with a petrol vehicle. The energy provided by one litre of petrol is converted into two things. One part is converted into work by moving the vehicle over several kilometres, increasing the vehicle's kinetic energy. But another part is converted into heat, either from the engine (which heats up) or the air surrounding the vehicle (due to friction). If we brake the car, we can recover some of the work invested in keeping the vehicle running (with a dynamo) to charge a battery (in fact, this is commonly used by hybrid vehicles: braking helps to charge the batteries). But a large part of the energy contained in the fuel has been transformed, in one way or another, into heat, either during the car's journey (friction, heat dissipation of the engine) or during braking (heating of the braking system due to friction of its components). This heat cannot be recovered to charge a battery.

In this way, the combustion of petrol in the engine to obtain mechanical work is an irreversible process, where many dissipative phenomena are involved, as a significant heat flow is generated and dispersed in the environment. The energy in the fuel has not disappeared, but it has become essentially useless. Only a small fraction of the initial energy has been able to make the round trip, being transformed first into mechanical work that increases the kinetic energy of the car and then transformed back (during braking) into chemical energy in a battery that will be used for more work in the future. On the other hand, most of it has been irretrievably transformed into another form of energy (dissipated heat) that is utterly unusable for future mechanical work. It has flowed into the colder environment and dispersed into the atmosphere. We will no longer be able to recover it.

Exergy

Exergy measures precisely the maximum amount of mechanical work that can be obtained from a system, i.e. the part of the energy contained in that system that can be used to "do something with it" by converting it into mechanical work (Brodianski 1990, chap. 3,4).

From another perspective, exergy would be the minimum amount of energy required to form a system from its constituent elements found in a reference environment. The "minimum" comes from the fact that exergy is the energy required to form the system using a reversible process, a theoretical process in which no dissipation would occur (Valero, Valero, and Calvo 2021, ch. 4).

Since the energy in a reversible process is not unused because there is no dissipation, the two meanings of exergy are equivalent: the minimum amount of energy required to form the system (i.e., through a reversible process) is equal to the maximum energy that the system has available to be transformed into mechanical work through a real process.

The second principle of thermodynamics can be expressed in terms of exergy as follows: in any process taking place under conditions of interaction with a balanced environment, the exergy of the whole system either remains unchanged (in ideal = reversible processes) or decreases (in real processes) (Brodianski 1990, chap. 3,4). The irremediable decrease of exergy is another way of saying that "energy goes from bad to worse.”

Entropy and the second principle of thermodynamics

Entropy was defined precisely to measure the "progress" of all phenomena in the sense of irreversibility. The aim was to obtain a metric of that progression made up of events that can never wholly happen "backwards".

Inspired by Carnot's work, it was Rudolf Clausius who, in 1855, gave the original definition of entropy (Rovelli 2018, ch. 2), based precisely on the example of heat that only goes in one direction and which so attracted Carnot's attention when he studied steam engines. Clausius equated this "irreversible transit" of heat to the variation of a quantity he called entropy. The change in the entropy of the system along the irreversible process (not its absolute value) was defined by Clausius as the amount of heat exchanged by the system with the surroundings divided by the temperature.

Clausius was also responsible for the original statement of the 2nd law or principle of thermodynamics: the entropy of an isolated system remains the same or increases but never decreases. Again, "stays the same" would apply to a reversible process, an idealisation that, in reality, never happens. The increase in entropy could also be interpreted as the increase in the amount of energy not available in a system for use in the form of work (Georgescu-Roegen 2021c). When entropy increases, there is more and more unusable energy, i.e. less and less exergy.

The second principle as increasing disorder

There is an interesting interpretation of entropy in terms of the disorder present in the organisation of matter. Let us imagine that we have a macroscopic system (for example, a certain volume of a gas contained in a container) in a given state, which we will call "A," and which is characterised by corresponding to a given temperature, pressure, and volume.

In thermodynamics, it is understood that there are a certain number of arrangements in which our gas can be organised internally (the different options for the gas molecules to be placed in the available space) so that the macroscopic observable state is the A state. This number of distinct microscopic arrangements, which generate the same macroscopically detectable state, is interpreted as a measure of the molecular "degree of disorder" of the gas in that state A. The fewer ways of internally arranging the system to present a given macroscopic state, the lower the degree of disorder associated with that state.

The analogy of a warehouse can be used here. There is only one warehouse stock arrangement compatible with the macroscopic state that we can call "warehouse in perfect order, with everything in its place". This is the state of maximum order when EVERYTHING is in its place. On the other hand, the state that we could call a "warehouse in a mess" is achievable with a multitude of internal arrangements of the warehouse stock. There is only one way for everything to be in order, but many (and all of them equivalent in terms of the appearance of the whole) for everything to be in disorder. This is how the number of internal arrangements of the system compatible with a given macroscopic state measures the degree of disorder we can associate with that state.

For another example (Feynman 1963, ch. 46), suppose the gas we discussed earlier consists of black and white molecules, and the space available for the gas is divided into small volumes or cells so that each molecule is placed in one of these cells. How many ways can we distribute the molecules among the available cells so that all the white molecules are on the left side of the container and the black molecules are on the right? On the other hand, how many ways could we distribute the black and white molecules in the available cells, with no restriction on where each goes? There are many more ways to distribute the molecules in this second case when we do not impose any restrictions. This state (black and white molecules mix in any way) is messier because it admits more internal configurations compatible with the same macroscopic state. So, it has more entropy. In contrast, the state where all the white molecules are on one side and the black ones on the other can be achieved with fewer different arrangements, so it is a more ordered state with lower entropy.

Now we have a small problem. It is reasonable to understand that entropy is related to disorder. But the fact is that the original definition of entropy, that of Clausius, does not speak of disorder, but of heat exchanged between the system and its environment. It does not even allow us to know the absolute level of entropy in a given state, but only the increase in entropy that the system experiences when it moves from one state to another, based on the heat it exchanges with the outside world during this transition.

Ludwig Boltzmann offered the solution to this question in 1865. He did so while laying the foundations of statistical mechanics, a field of physics that attempts to deduce the thermodynamic properties of macroscopic systems by analysing the motions and interactions of the fundamental (microscopic) particles that compose them. Statistical mechanics precisely measures the entropy associated with a given state related to the molecular disorder corresponding to that state. It's just what we need.

According to Boltzmann's expression, the system's entropy when it is in state "A" is proportional to the logarithm of what is known as the "thermodynamic probability," which is simply the number of internal arrangements compatible with the external state "A" (Pathria 1996). Thanks to this formula, we already have an entropy defined for each macroscopic state as a function of the number of internal arrangements compatible with that state, i.e., as a function of its degree of disorder.

Entropy understood as the degree of disorder of matter, connects easily with irreversibility since any irreversible process implies an increase in molecular disorder. Dissipation, dissolution, mixing... all these increase the degree of agitation of molecules, their unorganised energy, and their entropy (Zemansky 1973, ch. 10). If entropy measures the degree of disorder, its increase measures the disordering of matter. Thus, irreversible processes can be characterised by increasing molecular disorder.[3]

Under this approach of entropy as the degree of disorder, the second principle of thermodynamics (the one that states that entropy increases) would conclude that the universe tends to increase its disorder. The becoming, which is nothing but an enormous succession of small interactions, each governed by the laws of physics, leads the world to more probable states, those attainable with more internal configurations—states that are ultimately more disordered in the thermodynamic sense, with greater entropy.[4]

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[3] Everything also fits between Boltzmann's formula for the entropy level (as a degree of disorder) of the system when it is in state "A" and Clausius' formula for the change in entropy of the system when it exchanges heat with its surroundings as it transitions from state "A" to state "B". According to the Clausius formula, the system that absorbs heat by moving from state "A" to state "B" will increase its entropy. By absorbing heat, it will increase the thermal agitation of the molecules and thus their disorder. State B will be compatible with more internal arrangements of the microscopic particles that make up the system, so the "thermodynamic probability" in state "B" (the number of internal configurations compatible with state "B") will also be higher, which, according to Boltzmann's formula, indicates that the system has a higher entropy in state "B" than it had in state "A".

[4] Once it is understood why the world moves from order to disorder, an interesting question arises: why was the world more ordered in the beginning? This is neither a trivial nor a settled question. Feynman (1963, ch. 46) claims that this initial "greater order" is seen wherever you look in the universe with a telescope, so it is a "universe-wide" thing. As Feynman says, "That does not mean that we understand the logic behind it. For some reason, the universe once had very low entropy for its energy content, and since then, the entropy has increased. So that's the path that awaits us in the future. That's the source of irreversibility. For his part, Rovelli (2018, ch. 2) argues from the realm of relativity and risks an answer: the particular is not in the world but in us and our interaction with it. The increase in entropy that we detect as law would result from our particular way of interacting and interpreting the world, which is our doing rather than the world's.

The second principle as a decrease in the amount of information

A final interesting interpretation of entropy indicates that the number of modes (internal arrangements) that make it possible to reach a particular macroscopic state (the number to which entropy is related) also indicates the information we have at our disposal about that system. Let us see why. The internal arrangement of the system (the exact position in space each of its microscopic components occupies at a given moment) cannot be known; it is impossible to determine. So, knowing the macroscopic state (the external "appearance" of the system in terms of its basic thermodynamic variables such as volume, pressure or temperature), the most we can say is that the internal arrangement will be one of all those that are compatible with that state that we can observe macroscopically.

The greater this number of compatible internal arrangements, the greater the entropy because the greater the range of possibilities in which our system could be placed without our being able to determine exactly which one it is in (since all of them result in the same macroscopic appearance). So, our lack of knowledge about the microscopic state of the system is greater. Conversely, the fewer internal configurations compatible with the macroscopic state, the more information we have about how the system is (Zemansky 1973, ch. 10), in the sense that we have less uncertainty about how it is arranged internally (fewer options available).

Entropy would be accounting for the extent of our ignorance about how the system is internally arranged. In Brillouin's words, "entropy measures the lack of information about the exact state of a system" (Zemansky 1973, ch. 10).

The flow of time and the paradox of reversible laws causing irreversible phenomena

Something differentiates entropy and the second principle of thermodynamics from the rest of the magnitudes and laws of physics. It has to do with the concept of time. In the nineteenth and twentieth centuries, physics, when it asked itself what time was, came up against something very disconcerting: the difference between past and future does not exist in the elementary laws that describe the mechanisms of the world (Rovelli 2018, ch. 2). Neither Newton's mechanics, nor Maxwell's electromagnetism, nor Einstein's relativity, nor Dirac's and Schrödinger's quantum mechanics differentiate past from future. All these equations have the property that if there is a solution (i.e. a possible phenomenon) for a time "t", there is also another solution for a time "t".

Therefore, it would seem that the world is reversible in the equations of physics. Everything that happens and is described by the above-mentioned fundamental equations could perfectly well happen backwards, as far as these equations are concerned. Nothing in the equations prevents it.

But the fact is that the most natural characteristic of all real phenomena is their obvious irreversibility (Feynman 1963, ch. 46), i.e., that phenomena happen in the temporal sense in which they occur, which is a particular one and cannot happen in the opposite sense. This is part of our "common sense" as humans. Imagine we watch a video where a hand shakes a container containing raw beans and chickpeas. As the video progresses, we see the chickpeas cluster at the bottom of the container and the beans at the top. Is this credible? No, we know perfectly well that we are being deceived and that the video is projected backwards. The "unmixing" does not occur as a result of the shaking. Experience tells us that things spontaneously tend to mix, not to separate their constituent elements. Mixing is a highly irreversible process that only happens in one direction, along which the entropy (disorder) of the system increases as the components mix, never the reverse.

But where does the irreversibility of the second principle of thermodynamics come from if all the fundamental physics equations are temporally reversible? Why does this irreversibility only become apparent when heat comes into play, somehow? Does it mean that the only genuinely valid theory of physics is thermodynamics? This does not seem to be the case since all the other theories mentioned, from relativity to classical and quantum mechanics, are amply supported by empirical evidence. Yet, they do not seem contained in the evident and ubiquitous phenomenon of irreversibility. As far as these equations are concerned, reversibility would be fully possible.

The solution seems to be that there is no conflict. The irreversibility of the world does not come from (nor does it require) a breach of the (reversible) laws of physics but from the fact that, by applying these laws many times to small components of matter, what happens macroscopically is a transition from order to disorder, which is the essence of irreversibility. For example, in a gas, each collision of the particles would be governed by reversible laws of mechanics, but if we start with a compartment separated into two halves with two gases, one on each side of the separation, and eliminate the separation, the reversible collisions between molecules of one side and the other end up generating an irreversible process that is the mixture of both gases.[5] The reversible laws governing each of the small interactions that fill the flow of time generate an irreversible current towards greater disorder.

Balance

We have a description of the phenomena of energy and heat that works well in physical reality. This description has two complementary pillars: a microscopic one, statistical mechanics, based on the equations of mechanics applied to the microscopic components of a system, and a macroscopic one, thermodynamics. Both fit together.

From this description, we deduce in practical terms a principle of irreversibility, in the sense that every physical system evolves in a way that is called irreversible. We understand irreversible in the sense that the process could not go in the opposite time direction to the one it is taking.

This irreversible happening of the universe as a whole (or of any system that we can consider isolated), over time, presents three symptoms or can be described from three alternative and consistent perspectives, which are none other than the three ways of stating the second principle of thermodynamics.

The first symptom is the decrease in the amount of usable energy in the universe (the exergy) or, in other words, the increase of the unusable fraction of the present energy. The existing energy is always the same (the first principle of thermodynamics), but it is increasingly degraded in terms of its capacity to provide mechanical work (with less and less exergy).

The second symptom is the increase in molecular disorder, as the reversible laws of mechanics, operating in the microscopic, make the system evolve irreversibly to the most probable macroscopic states, those that are compatible with the greatest number of internal configurations of the system. The relationship between symptoms 1 and 2 is immediate since the amount of energy that becomes unusable in the course of an irreversible process is precisely

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[5] Curiously, Nicholas Georgescu-Roegen (2021d), the leading economist in terms of the consideration of entropy and the laws of thermodynamics in economics, disagrees strongly with statistical mechanics. For him, the second law of thermodynamics and its irreversibility reveal that the reversible mechanistic paradigm of classical mechanics had clearly been superseded by the mid-19th century. Statistical mechanics would have been a desperate attempt to save this superseded paradigm, using it to "microfound" thermodynamics. An absurd "collage" would thus have been generated: what is a universal law (the increase of entropy) is described in the field of statistical mechanics as the most probabilistically plausible outcome of the universe's evolution, but without ruling out the possibility of others. Indeed, for statistical mechanics, it is not entirely impossible for a glass of boiling water that has been cooled by contact with air to spontaneously boil again by stealing heat from the surrounding environment. But the probability of such a thing happening (which would violate the second principle of thermodynamics) for a macroscopic system (i.e. with many molecules) is negligible, for all practical purposes indistinguishable from zero. But the fact that it is not strictly zero is, for Georgescu-Roegen, proof that the spurious addition of statistical mechanics shakes the scaffolding of physics. Physicists, for their part, do not generally have any headaches with this question (Tipler 1994, ch. 17).

proportional to the increase in entropy that the universe has experienced as a consequence of that process (Zemansky 1973, ch. 9). And, in the same sense, the greater the entropy (disorder) in the system, the less exergy (usable energy) available to extract from it and transform it into mechanical work.

Finally, the third symptom is decreased information available about the system, which is the flip side of increased disorder. The greater the number of configurations compatible with a given macroscopic state, the greater the entropy (, the greater the disorder), but at the same time, the less we know about the system because we only know that it will be arranged internally according to one of the (many) arrangements compatible with the macroscopic state we observe.

In short, the arrow of time points in the direction of increasing entropy and disorder, or in other words, decreasing exergy or usable energy. This is what physics describes. And the description works.

The economic system and entropy

Life and entropy

Before we get to economics and sustainability, we have to make a short, intermediate stop at " what is living ". What is the relationship between entropy and life? Schrödinger, one of the pioneers of quantum mechanics, was one of the first to investigate this question (Schrödinger 1990). The truth is that living matter is more ordered than inert matter, so it has less entropy. Life struggles to maintain its low entropy, absorbing low entropy from the environment and expelling high entropy into it, fighting against its inherent tendency to increase its entropy, which would happen if it died (Georgescu-Roegen 2021c).

Life accelerates the entropic growth of the system of which it is a part, "stealing" low entropy from its environment in the form of energy and materials and returning heat and waste of increased entropy to the system to maintain itself as the low-entropy island that it is.

It would seem then that the existence of life violates the principle of entropy increase, or at least opposes it. It is instead the opposite. Life accelerates the entropic growth of the system of which it is a part, "stealing" low entropy from its environment in the form of energy and materials and returning heat and waste of increased entropy to the system to maintain itself as the low-entropy island that it is. But the net entropy balance is positive. The entropy of the whole system (life + environment) grows faster because there is life.

Thus, the law of entropy does not explain the existence of life, nor does it need life to be fulfilled. But life does not contradict the law of increasing entropy. Still, it helps it to be fulfilled more rapidly (Georgescu-Roegen 2021c), accelerating, as a means to subsist, the degradation (entropy increase) of the system of which it is a part.

On this starting idea, Schneider and Sagan develop their explanation of the (physical) meaning of life in their book The Thermodynamics of Life (Schneider and Sagan 2008). For them, life is one of many complex self-organised systems (i.e. with lower entropy than its surroundings) that arise in nature in the heat of so-called "gradients", which are simply differences in the value of a magnitude over a distance.[6]

The truth is that nature seems to abhor gradients, as it gives rise to many types of organised structures to "flatten" them. A tornado would be an example of an organised (albeit non-living) structure that "manages" an imbalance of atmospheric

[6] For example, there is a vertical temperature "gradient" in the atmosphere, because as we ascend above the earth's surface, the air temperature changes.

pressures, contributing to its demise. Well, life on Earth would also be one of these systems, particularly complex, which would contribute, fed by the flow of solar energy, to "flatten", to homogenise the tremendous thermal gradient that exists between the Sun (hot) and space (cold). Life on Earth helps to degrade solar energy more efficiently.

Physicists like Schrödinger called "non-entropy" or negative entropy what feeds life, what life requires to exist (Schrödinger 1990). Exergy allows us to speak of the same, of what "eats" life, but in measurable magnitudes in units of energy (Brodianski 1990, ch. 4).

So being alive consists, thermodynamically speaking, in keeping your entropy low. The paradox is that, in doing so, you "consume" the source of your subsistence, which is the low entropy you extract from your environment. Life effectively degrades (more effectively than non-living matter) the low entropy that makes it possible. That is the loophole left by the laws of physics for something as improbable as life (because of how organised it is) to come into existence: it accelerates the process of disorganisation of the universe in general.

Economics and entropy

Following the thread of entropy, it is now time to make the leap from life to economics. Nicholas Georgescu-Roegen is undoubtedly the one who has worked most actively on this topic (Georgescu-Roegen 1971; 2021c; 2021a; 2021b; 2021d). We will first explain Georgescu-Roegen's view of the economy as an extension of the living and then analyse the sources of low entropy that feed the economic system.

The economy as an extension of the living

The economy can be understood as a vital activity of human beings, an extension of the biological functions of our species. To survive, human beings do not limit themselves to using (as all living beings do) their endosomatic (internal) organs, perfected by natural selection, but have also invented and perfected (through cultural transmission) tools and ideas, which can be considered exosomatic (external to the body) organs. These enable the species' needs to be met well, although their production, distribution and control give rise to inevitable social conflict (Georgescu-Roegen 2021a).

> *The economy feeds low entropy as organised matter and usable energy and constantly expels high entropy back into the system in the form of less organised matter (waste) and less usable energy, dissipated as heat.*

The economy is also an extension of "the biological" as far as entropy is concerned: the economy contributes to the increase of entropy in the system as a whole. To this end, it feeds low entropy in the form of organised matter and usable energy (both from other forms of plant or animal life and mineral resources) and constantly expels high entropy back into the system in the form of less organised matter (waste) and less usable energy, dissipated as heat (Georgescu-Roegen 2021c).

> *Entropy has not been recognised by traditional economics, which often represents economic activity as a closed production-consumption circle and, even worse, without any intervention of natural resources.*

However, this has not been recognised by traditional economics, which often represents economic activity as a closed production-consumption circle and, even worse, without any intervention of natural resources. The only closed scheme that could reliably represent the economic system would be that of an hourglass, in which "high quality" matter and energy, low entropy resources, occupy the top of the clock. Over time, the resources are processed by the economic system and transformed into different, lower quality, higher entropy resources, which fall to the bottom of the clock. This is an irreversible process, so the resources, when they reach the bottom, are degraded, have gained more entropy and are therefore no longer usable to the same extent as they were before when they were at the top of the clock (Georgescu-Roegen 2021a).

It is true that human production sometimes consists of reducing the entropy of a given material to build a more organised material with lower entropy. An example, taken from Georgescu-Roegen (2021c), would be to manufacture copper wire from copper ore, a process in which the entropy of the copper material decreases (since copper wire is more organised, less entropic matter than the ore with which the process began). But that is not the whole story. Energy has been invested in this industrial transformation, and machines have been used and had to be built. All in all, the process of manufacturing copper wire, although it generates an "island" of decreasing entropy (that of the copper wire itself), contributes, in aggregate terms, to the entropy of the universe increasing more rapidly than if this process had not taken place.

So, the economic system plays a role similar to that played by the metabolism of life: accelerating the entire entropic degradation of the system. As an extension of human life activity, the economy also generates "islands of low entropy", more organised material structures. Again, this does not oppose the law of entropy increase but, on the contrary, accelerates its inexorable fulfilment in the system as a whole.

Sources of low entropy for the economy

For Georgescu-Roegen (2021c), the "low entropy" that feeds the human economy comes from two sources. On the one hand, the stock of materials that the Earth offers us, which includes the fossil fuels and minerals we use as the material basis of our subsistence; on the other hand, the flow of solar radiation.

This classification is a good starting point but has at least two drawbacks. The stock/flow dichotomy is evident, but it hides a critical issue: the different nature of the two major items within the stock of materials provided by the Earth. Fossil fuels originated from solar energy that reached the Earth millions of years ago, whereas the minerals we use as materials did not. In other words, part of the stock of materials is actually "concentrated and packaged sunshine". Another relevant aspect missing is the role of non-human life as an irreplaceable mediator between our species and some of the most important sources of low entropy we need.

To design a classification that overcomes these limitations, one can start with two basic criteria: whether the entropy source is a stock or a flow and whether the origin is solar. This allows us to draw up a double-entry table, which we will begin to fill in by thinking first of all of the low entropy sources that human life requires for its most basic subsistence, everything that is essential to sustain our "endosomatic" part, our organism: food. From it, we obtain the materials and energy necessary to maintain our organism with the adequate (low) level of entropy it requires (figure 1).

Food requires the input of different sources of low entropy.

Food requires the input of different sources of low entropy. Its basis is in plant and animal life, so the first element that comes into play is a flow of solar origin: the sun's energy that we can only assimilate once it has been "processed" by plants (or by animals that ultimately feed on them). We can also consider the freshwater that life needs to survive due to the flow of solar energy. Solar energy from the (mostly salty) water available on the planet causes the evaporation that produces the rain that provides the flow of freshwater that life needs.

But human nutrition also requires low entropy, non-solar inputs. Regarding stocks, this involves the inorganic chemical substances that constitute the substrate for life and the media in which life develops (water - both liquid and gaseous -

and atmospheric air). Regarding flows, mention must be made of the geothermal energy that sustains some life forms (those living on the seabed, along mid-oceanic ridges, or inland areas with strong volcanic activity). The assumption adopted here is that all life forms are related. Thus, since some living organisms sustain food, it depends on all low entropy sources used by any life form.

Figure 1. Sources of low entropy for human life through food

	Solar origen	**Otherorigen**
Stock		- Minerals (material substratum of life) - Environment for life (fresh/salt water, atmospheric air)
Flow	- Solar energy processed by plant and plant and animal life that we use for food - Fresh water (consumed by living organisms)	- Geothermal (non-human life)

Prepared by the author

Having identified the low entropy sources that our endosomatic organs require as a minimum condition for subsistence, the table can be completed with those other sources that humans use. Evidently, these also serve to satisfy human needs, but in a much more organised way through more complex social structures and dynamics.[7]

In terms of low entropy sources of solar origin, we would, first of all, have fossil fuels, the stock of "sunlight batteries" that since the industrial revolution has sustained, albeit with varying degrees of intensity, the functioning of the vast majority of human societies (Figure 2, below). Additionally, in the solar origin column, but in the flow row, all the energy that reaches us through sunlight in the form of different "renewable sources" such as solar, wind, hydroelectric, or biomass combustion is added.[8] This also includes ripple energy provided by waves (which are mainly generated by wind, i.e. ultimately solar energy) or the energy provided by ocean currents, which are also derived from the sun as they exist mainly to redistribute the uneven flow of solar energy reaching each point of the ocean around the globe.

Directly or indirectly, all of the above sources provide low entropy, which comes from the luminous flux that reaches us from the sun. To complete the list of low entropy flows of solar origin, we must mention tidal energy, which originates in the movement of the tides. Part of this energy comes from the sun, not from the radiation flux it emits, but from the gravitational force with which it attracts the earth, which is one of the factors responsible for tidal movements.

[7] For example, both plant life and oil are low entropy sources that human society currently needs to survive as we know it. Both sources are essential for the most basic thing: food. It is not in vain that at the basis of human food is the cultivation of vegetables with intensive technology in the combustion of petroleum derivatives (at least in some areas of the planet). But there is a substantial difference between the two sources. Plant life is essential as a source of low entropy. Oil is not. Humankind has fed itself (but under what conditions) for thousands of years without mastering the technology of the combustion engine. Still, plant life has always been there, inevitably, as the basis of human subsistence.

[8] By definition, solar thermal and photovoltaic energy comes directly from the flow of sunlight. But so do all other renewable energies, albeit indirectly. Wind energy comes from wind, which arises from pressure differences in the atmosphere, resulting from the unequal amount of sunlight energy each point receives. Hydroelectric power comes from water that evaporates under the action of solar radiation, forms clouds and turns into liquid water which, if it falls on land areas high above sea level, tends to flow "downhill" towards the sea. We use this transit back to the sea to produce electricity. Biomass, as living matter, is also "packaged sunlight", just like the plant life that feeds us. Biomass has some stock elements, albeit short-lived compared to coal or oil. However, the biomass supply can also be seen as a solar flux "delayed" by a few years, which is the years involved in the growth of plant matter.

Figure 2. Low Entropy Sources for Human Life

	Solar origen	Other origen
Stock	- Petroleum-based materials (plastics) - Fossil fuels	- Minerals (energy) - Minerals (materials) - Minerals (material substratum of life) - Environment for life (fresh/salt water, atmospheric air)
Flow	- Solar energy processed by plant and animal life that we use for food - Fresh water (consumed by living organisms)	- Geothermal (non-human life)
	- Biomass (energy and material) - Solar energy (thermal and photovoltaic) - Aeolian energy - Hydroelectric energy - Marine energy due to sunlight flux (wave and currents) - Tidal energy (solar gravitational force)	- Geothermal energy (human use) - Tidal energy (lunar gravitational force)

Own elaboration (shaded area: low entropy sources on which human food depends; green: low entropy sources that we use with the mediation of non-human life).

Still, in the column of solar origin, there are two additions to the material, not energetic, sphere. The first is a stock: the materials we get from oil, such as most plastics. The second is a flow of all the materials we obtain from plants, from wood for constructing all kinds of objects and structures to plant-based materials with which we are timidly finding substitutes for some traditional plastics. This constitutes the third appearance of plant life or "biomass", first as food, then as a source of energy, and now as a source of materials.

In the column of non-solar origin, we place, to begin with, the stock of minerals that we extract from the Earth's crust. These materials do not constitute a "sunlight pile" like fossil fuels but are made up of chemical elements formed in stellar combustion, recombined in some cases by geological processes where the energy input, if any, has come from the Earth's geology through volcanism and tectonic movements.

In the case of materials, "low entropy" refers to the degree of order we need them to contain. For example, if we need lithium for batteries, we need to find a lithium mine where this chemical element is in a relatively organised form, sufficiently concentrated that it is feasible and profitable to extract material from the mine and then obtain the lithium element from it. If all the lithium on earth were completely dispersed throughout the earth's crust, in nanogram particles mixed in with the rest of the materials, we would have a problem. There would be lithium, but it would need to be better organised, with high entropy, very unusable. Accessing such entropic material would require enormous time and energy consumption to "select" it and separate it from the rest. In other words, we depend on these low entropy "reservoirs" as organised, non-dispersed materials to extract and use them in our production system.

These materials are of interest to us, in general, because they provide the material basis of our economy, with which we build our "exosomatic organs" (machinery, tools, everyday objects), in Georgescu-Roegen's words. This is the case, for example, of iron, aluminium, copper, or the aggregates we use for construction. But we should remember that a small part of these mineral resources of non-solar origin is of interest to us for the energy they can provide, as is the case with the mineral resources from which we obtain fuel for nuclear power stations.

Finally, in this same column of non-solar origin, some energy flows are of lesser importance in global terms. An example would be geothermal energy, which is suitable for human use. Countries such as Iceland provide energy for domestic and industrial use, such as aluminium smelters. This energy is of geological origin, unrelated to solar energy, and constitutes a heat flow which, because of its intensity, is suitable for producing work before dissipating into the atmosphere. Another example would be tidal energy due to the moon's gravitational pull.

The whole picture of low entropy sources (Figure 2) provides some interesting insights for the sustainability discussion. The first is how diverse the sources of low entropy that sustain human life are, even if we look at their minimum core, which forms the basis of our food supply (shaded cells in Figure 2). Here, we find fluxes originating from solar radiation and both stocks and fluxes of non-solar origin. This diversity is not surprising. Life does not waste any of the available low entropy sources to reduce the thermal gradient between the sun and space effectively.

The second idea points to the relevance of " the living " as a source of low entropy (green text in Figure 2). Not only is food entirely based on life, but life also makes a decisive contribution to human societies as a source of "exosomatic" energy through the energy that comes from burning plant matter and, most significantly, from burning fossil fuels. Vegetables (current and past, converted into oil) also provide abundant materials. It is no exaggeration to say that human life is inevitably intertwined with the rest of life on earth, both current (food, biomass for energy or materials) and past (fossil energy and materials).

The third idea considers the variety of low entropy sources already mentioned but now focuses on another facet: dependence. We draw negative entropy from many sources, i.e. we have a diversified range of suppliers. That sounds good, but the problem is that the sources are not, or only to a minimal extent, interchangeable. There is no substitute for the low entropy input we literally ingest when we eat. Although the energy we derive from our metabolism ultimately comes from the sun, we need the prior work of plants to be able to harness it to keep us alive. Apart from food, even among low-entropy solar energy sources, substitutability is limited or at least uncertain. The energy intensity provided by fossil fuels is essential for some applications (e.g. maritime transport) and impossible, for the time being, to replace with renewable sources.

Economics and the second principle of thermodynamics

Everything that sustains our (entropic) economic system, as an extension of our biological scheme for survival, is found on Earth. As part of the universe, it is subject to the second principle of thermodynamics, which imposes an increase in the entropy of any isolated system (which exchanges neither matter nor energy with the outside) over time.

However, the Earth is not a thermodynamically isolated system but a "closed" one because it exchanges energy with the outside world: it receives sunlight, and some of this energy is reflected back into space. Nor are the various terrestrial subsystems that come into play here at different scales isolated: living beings of all kinds, human society, the biosphere, or the economic system. Each of them constitutes an open subsystem within the Earth since it can exchange matter and energy with its environment to keep its entropy stable at a sufficiently low level.

So what isolated system is such that it is doomed by the second principle to increase its entropy, and what role does human society and its economy play in such a system? It must be a system that includes the Earth, and that can be considered reasonably isolated from the outside because it exchanges hardly any matter or energy with it. Such a system could be the Earth with the Sun and a certain volume of space containing both. In such an isolated system, the second principle of thermodynamics will be realised: its entropy will increase. In it, we have a very powerful low-entropy emitting source, the Sun, a very homogeneous and high-entropy environment such as space, and the Earth, which exchanges energy with space and whose position in the middle of this very powerful energy gradient between the Sun and space gives rise to the formation of complex structures (such as life) whose thermodynamic sense is to flatten the gradient from which they feed.

We help fulfil the second principle because our accumulation of low entropy means that materials tend to become less and less useful. After all, they require more and more work to make them usable. Energy becomes less and less usable because, as it loses exergy, it is less and less usable for work.

In such a system, the second principle dictates that increasing entropy is inevitable. The living being, human society, the biosphere, or the economic system collaborate in this thermodynamic destiny of the isolated system in which they are inserted. Their strategy? To become islands of low entropy, the lower the entropy, the more organisation and complexity they acquire, at the cost of consuming the available low entropy (materials and energy) in the environment at a faster rate.

We help fulfil the second principle because our accumulation of low entropy means that materials tend to become less and less useful. After all, they require more and more work to make them usable. Energy becomes less and less usable because, as it loses exergy, it is less and less usable for work. This would happen just the same without life, without humanity, and without any economic system, but with all this, it happens faster. It is inevitable.

What sustainability is about

Sustainability is about more than whether we can escape the second principle of thermodynamics. That is not possible. Rather, it is about whether the conditions are met for complex structures such as human society and its economic system to endure over time while contributing to fulfilling the second principle. What are these conditions? Quite simply, they are that the available low entropy sources supply the "food" required to sustain the metabolism of (all) life and the economy at a sufficient rate, given the conditions on Earth.

Let's start with some good news. In the time span of several billion years that we are interested in (the remaining lifetime of the sun before it grows too large and overwhelms the Earth), there are some sources of low entropy that we can surely count on (blue text in Figure 3 on the next page): these are the non-life-related flows (both solar and non-solar), those that we can access without the mediation of other living things.

Now comes the bad news: neither the availability of stocks (of whatever origin) nor access to the energy flows (mainly sunlight, but also geothermal) that we currently use to exist, thanks to the intermediation of living matter, is guaranteed.

The danger is depletion in the case of stocks of fossil fuels (and materials derived from them) and minerals (for both material and energy uses). The factor that will lead to this scenario sooner or later is that stocks are finite and diminishing because we are (increasingly) dependent on them.

Figure 2. Low Entropy Sources for Human Life-1

	Solar origen	Other origen
Stock	- Petroleum-based materials (plastics) - Fossil fuels	- Minerals (energy) - Minerals (materials) - Minerals (material substratum of life) - Environment for life (fresh/salt water, atmospheric air)
Flow	- Solar energy processed by plant and animal life that we use for food - Fresh water (consumed by living organisms)	- Geothermal (non-human life)
	- Biomass (energy and material) - **Solar energy (thermal and photovoltaic)** - **Aeolian energy** - **Hydroelectric energy** - **Marine energy due to sunlight flux (wave and currents)** - **Tidal energy (solar gravitational force)**	- **Geothermal energy (human use)** - **Tidal energy (lunar gravitational force)**

Own elaboration (shaded area: low entropy sources on which human food depends; green colour: low entropy sources that we exploit with the mediation of non-human life; blue colour: low entropy sources that are secured in the long term)

More complex is the question of the low entropy sources we currently access by mediating non-human life. The flow of sunlight that feeds life will be available, but there are two threats. One is that exploiting some forms of life, whether for food, energy or materials, will lead to their disappearance. One example is fishing. Like all living things, fish have a specific dynamic of perpetuation over time. If we exploit this low entropy form at an excessive rate, it will simply disappear, a phenomenon that is already evident in the delicate situation of certain fish species in some fishing grounds. Another example is logging trees at a rate that exceeds the rate at which forests can regenerate.

The second threat concerns the non-solar stocks on which life depends (mineral substrate and environment - water and air). The risk here is not depletion but rather that the cycles that regulate the availability of critical elements such as phosphorus and nitrogen will be broken or that water (fresh and salt) and/or atmospheric air will lose the characteristics (composition, temperature, salinity, acidity, etc.) that make life possible. Life evolved and adapted to these stocks with certain conditions, and sudden changes in these stocks (and decades or centuries is a very short time in evolutionary terms) compromise the survival of life.

> *If we consume the life we feed on too quickly this form of low entropy will no longer be available. And if the low entropy stocks that nourish life are no longer adequate to fulfil their function (through pollution), the problem will be the same.*

The dangerous factor in this respect is pollution, in whatever form. Here are three examples. The accumulation of mercury can poison an ecosystem, the overuse of fertilisers can unbalance seawater conditions by modifying the availability of oxygen for some species, and, finally, the accumulation of greenhouse gases and the climate change it causes, with the consequent rise in temperatures, can seriously hamper life in certain environments. All these circumstances can lead to changes that potentially compromise our ability to access food, i.e. to access all the low entropy sources in the shaded area of Figure 3 (and also biomass), to the extent that they strain the living conditions of all organisms (affecting the stocks on which they depend).

In other words, if we consume the life we feed on too quickly (overfishing or deforestation), this form of low entropy will no longer be available in the future, and if the low entropy stocks that nourish life are no longer adequate to fulfil their function (through pollution), the problem will be the same. Either way (consuming life or making life's subsistence unviable), we would lose access to all the low entropy flow originating in sunlight that we now access through non-human life (bottom left box, green text), either for food or for energy and material uses from biomass.

In view of the above, long-term sustainability is only possible if three quite demanding conditions are met.

In view of the above, long-term sustainability is only possible if three quite demanding conditions are met. On the one hand, we must be able in the future to obtain all the energy we need from sunlight, tidal and geothermal energy flows (those that are guaranteed in the long term, blue in Figure 3) because the sunlight piles, which is essentially what fossil fuels are, are finite. Currently, we do not meet this condition. We are consuming this low entropy source (coal, oil and gas), an unrepeatable geological gift for which we currently have no substitute, although we may be able to find one.

The second condition is analogous to the previous one but refers to the minerals on which the material survival of our societies depends. Here again, we are depleting (perhaps more slowly, though it is difficult to determine) a low-entropy source that has been given to us. This is another geological gift that we are taking bigger and bigger bites of as our material demands increase.

The third condition is that we must be able to avoid damaging our economic metabolism, the cycles and conditions on which life on Earth depends, on whose health our food, i.e. our survival (as well as the energy and material services provided by biomass), inevitably rests. We are not doing this either. We are also damaging, by overexploitation and/or by altering environmental conditions, a key source of low entropy, such as the biosphere. Its importance, especially as the exclusive source of our food (shaded cells in Figure 3), is that there is no substitute for it. Even if we could achieve excellence in capturing solar energy for industrial uses, humans would not last long without plants. We simply cannot "eat sun".

Put simply, to achieve sustainability, we should, in the long term: i) get rid of energy dependence on one non-renewable stock (fossil fuels) by making do with renewable energies, which are flows (solar and non-solar); ii) avoid the depletion of another non-renewable stock, that of mineral materials for which we have no substitute; and iii) avoid damage to the biosphere which, as an exclusive source of food, has no substitute.

The key to sustainability lies in the fulfilment of the above conditions. A novel factor in terms of human history adds a little more urgency to the scenario: climate change. It is a consequence of a type of pollution, collateral damage of our development based on the combustion of coal and oil, which further complicates the fulfilment of the above three conditions. Because it makes life on earth more difficult (because it forces organisms to function in a rapidly changing environment to which they cannot always adapt), it

It is no longer a matter of "not harming" the biosphere but rather a "repair" of the damage already done.

compromises our ability to feed ourselves. This increases the demands of meeting the third condition: it is no longer a matter of "not harming" the biosphere but rather a "repair" of the damage already done, which makes it more difficult.[9]

In addition, climate change will likely make the planet a more inhospitable place for human life as we know it, with greater uncertainty and risks. More frequent extreme weather events, which we are already experiencing, may mean more energy expenditure to cope with more extreme temperatures (more intense peaks of cold and heat in hitherto temperate and highly populated areas), i.e. an added difficulty in meeting condition 1. But it also means that more will have to be invested in building new infrastructure and repairing existing infrastructure to adapt to the new situation, which means more use of materials, i.e. more difficulty in meeting condition 2.[10]

Climate change, to the extent that it causes increasingly obvious effects (they are already beginning to be so), would be "moving the finish line further away," i.e., complicating the sustainability task and making it more challenging to meet the three conditions above.

To sum up, the reality seems to be that our current dynamics do not exactly bring us closer to a sustainable scenario. We are heavily dependent on exhaustible fuels and materials, sources of low entropy that are only partially substitutable with current technology; we are damaging the biosphere (our access route to irreplaceable sources of entropy), altering the environmental conditions and basic cycles that life requires; and we are provoking climate change that may exacerbate the above dynamics, increasing the demands on non-renewable stocks, and making the biosphere a very different place in a few decades, a less friendly place for a life whose capacity for adaptation is ample, but not unlimited.

We come then to the vital question of sustainability, which encapsulates all of the above. Given the current dynamics that will lead us in the long term to a progressive depletion of fossil fuels, to a progressive (though not so pressing) scarcity of readily available materials, and to ecosystems increasingly stressed by pollution, will we be able to feed ourselves while the sun satisfies our low entropy energy demand for heating, cooking, recycling the materials used and adapting to the consequences of accumulated pollution?

What kind of society must we be in order to meet the three conditions set out above?... How can humanity reach that scenario alive?

That is the question. To answer in the affirmative (that is the goal!), we have to resolve two questions, each more difficult than the other. The first concerns the long-term future that we must imagine for humanity to be viable: What kind of society must we be in order to meet the three conditions set out above? In other words, what must this future look like for humanity to be sustainable?

Even if we know the answer, there is a second, even more pressing question because it challenges us for the "here and now": How can humanity reach that scenario alive? To put it another way, assuming we know what the future we need looks like, how do we get there? How do we manage now to move successfully towards sustainability without being derailed by one of the many dangerous curves that are sure to emerge?

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[9] This, by the way, also applies to other types of pollution, such as microplastics. We are no longer in a situation where we aim to "do no harm" because there have already been significant alterations. So, in many cases, it is a matter of "minimising damage" or even reversing it.

[10] To close the circle, the remediation of environmental damage to which we have referred is not free either, as it involves using material and energy resources, so again, there are more difficulties in meeting conditions 1 and 2.

In light of these two questions and all that has been said in the previous sections, two conclusions emerge. First, sustainability is relevant; it is about whether we are viable as a species in the long term. Second, energy, material resources and waste must be integrated to analyse this question. At least, this is what a glance at the list of low entropy sources in the previous section suggests. Let us see why.

Regardless of their origin (solar or non-solar) and their presentation (stock or flow), all low entropy sources within our reach serve to provide us with two inputs: matter and energy with a suitably complex organisation to sustain (and endure) our complexity (low entropy) as a life form. But both inputs inevitably work together. Capturing low entropy in the form of energy (e.g. extracting fossil fuels) requires material structures. In turn, extracting materials requires intense energy inputs. We cannot think of satisfying energy needs without material needs, nor vice versa. The two are strongly connected.

On the other hand, the production of matter and energy, whether as an individual organism or as an economic system, always involves waste production. These wastes, high entropy materials resulting from our metabolism, remain with us, do not disappear, and may compromise the availability and quality of other low entropy sources (for energy or material use) in the future, even in the short term. It is worth recalling two examples that have already been mentioned. The first is pollution that threatens the health of ecosystems, on which our food supply, that irreplaceable source of low entropy, ultimately depends. The second is a particular type of pollution, greenhouse gases, which stress ecosystems and change the energy and material requirements of human society.

So waste, pollution, residues, whatever we want to call them, neither disappear nor are they unrelated to the question of energy and materials. Reducing them would seem a good idea, but how? We could reduce the intensity of metabolism (the famous "degrowth"), but would this be socially acceptable? Another option is not to take waste for granted and try to use it, but this is not entropically free. Recycling is energetically costly and implies a material cost to design the industrial infrastructure where this task is carried out. We could also be more efficient in producing less waste (e.g. by reducing CO2 emissions in terms of climate change), but this also has an entropic cost. Transitioning from a fossil energy-based economy to a renewable energy-based economy is technological uncertainties aside, a fossil energy and very specific materials-intensive process (rare earth).

> *Energy, materials and pollution are three inseparable sides of the single entropic process of economic metabolism —three intertwined areas in which humanity's viability is at stake.*

Economics and sustainability: issues, questions and some references

As we justified in the previous section, what we do in any of these three areas - materials, energy and waste - has consequences for the other two. Without losing sight of this fact, a structured list of the relevant areas of analysis is proposed below in three content groups: present issues we need to understand better, questions that have to do with the long term, and finally, questions that refer to the short and medium term.

Issues we need to understand better

To begin with, we need to deepen our understanding of the three facets of sustainability: materials, energy, and pollution. In terms of materials, the basic technical question concerns their extraction: how it is done, what technology is required, what are the environmental effects of the mining activity, etc. (Valero, Valero, and Calvo 2021).

In terms of energy, we need to understand better the different energy sources and their characteristics: from the most energy-dense but difficult to control (nuclear) to those with lower energy density but which are very difficult to concentrate and store (solar) to fossil fuels, which, apart from their collateral effects, offer benefits that are difficult to match: high energy density, easily controllable and storable (Georgescu-Roegen 2021d; González Reyes 2022). It is also necessary to know where we are regarding fossil fuels, with the discussion as to whether or when the peak production has already been reached (Turiel 2022).

A fundamental issue is that, at the moment, we can only obtain non-fossil energy if we have fossil fuels in the backroom.

It also seems necessary to know the history of humanity and energy (Fernández Durán and González Reyes 2018a; Smil 2021), as well as, with that historical perspective, the challenges we are currently facing in terms of energy (Smil 2022). A fundamental issue is that, at the moment, we can only obtain non-fossil energy if we have fossil fuels in the backroom. Neither nuclear reactors nor solar panels can be made without fossil fuels. Solar panels are not meant to produce more solar panels.

Concerning pollution, we must first mention the phenomenon of climate change, perhaps the most analysed area of sustainability to date and the one on which international science has worked most resolutely together to provide a constantly updated view of the state of the question and future prospects (Bennett, 2019; International Panel for Climate Change 2022; Lomborg, 2021; W. D. Nordhaus 2013; Thunberg, 2022; Wallace-Wells 2019). But this is not the only effect of pollution. The planet would have various boundaries associated with the cycles of some chemical elements and the capacity to withstand foreign particles such as plastics and other entities., many of which would have already been exceeded, as detailed in the Nature article by Rockström et al. (2023).

In addition to materials, energy and pollution, a fourth issue we need to understand better is the state of the scientific and technological frontier in areas relevant to sustainability. Two examples are developing more powerful and longer-lasting batteries that store electricity from renewable sources or the possibility of eventually obtaining energy from nuclear fusion. Finding a reasonable point between naïve technological optimism and hopeless energy collapse is impossible without gathering expert knowledge on these scientific and technological issues. Are breakthroughs that will change environmental constraints possible? Are they plausible? Is it possible to estimate timelines?

The environmental dilemmas we face are not the result of chance but of certain behaviours of the actors involved, operating under the incentives provided by the economic system, defined by a multiplicity of factors, such as the economic or political power structure or historical factors, among others.

Finally, it also seems relevant to understand how we got here. The environmental dilemmas we face are not the result of chance but of certain behaviours of the actors involved, operating under the incentives provided by the economic system, defined by a multiplicity of factors, such as the economic or political power structure or historical factors, among others. Without understanding why we have reached this point, it is difficult to reflect usefully on what to do.

Long-term questions

In the long term, questions arise that are just as, if not more, interesting. For the materials we mine, the main question is, of course, their possible depletion. Depletion does not mean that they will "disappear" but will cease to be available in the form we find them today, concentrated (with low entropy) in mines. Will there come a time when mining today will be transformed into so-called "urban mining", which would try to obtain materials from landfills where all the waste that is not burned will have been mixed for decades or centuries? What are the timescales before "easily extractable", i.e. low entropy, materials become scarce (Valero, Valero, and Calvo 2021; Valero, Calvo, and Valero 2022)?

Regarding energy, some questions are: In what timeframe is it plausible that fossil fuels will run out? If this depletion were to occur, would it mean the end of capitalism due to energy collapse (Fernández Durán and González Reyes 2018b)? Finally, the pollution analysis leads us to project, to begin with, the effects of climate change: will we be on the "inhospitable planet" predicted by David Wallace-Wells (2019)? Perhaps the problem will come from pollution other than greenhouse gases, related to the other planetary limits we already exceed (Rockström et al., 2023). It is clear that the Earth will continue to exist in such a polluted future, but the question is what restrictions the environment will impose on the living conditions of the humans who inhabit it. And, by the way, how far away is that future?

This brings us to a question that has taken on a life of its own as a field of analysis: the possibility of the collapse of human civilisation. This term does not have a closed definition. Sometimes, it would mean a "path towards disappearance", while González Reyes interprets it as a loss of complexity in the network of nodes that make up society (González Reyes 2021). For his part, Santiago (2023) points out that, in general, those who use this term are referring more or less explicitly to a society that survives but in material and political conditions that we could equate with those of a "failed state" in which, among many other problems, there may be difficulties or shortages in satisfying the basic necessities of the population.

"Collapsism" is becoming increasingly relevant in the field of sustainability.

Whatever the precise meaning we want to give to the concept of collapse, the fact is that "collapsism" is becoming increasingly relevant in the field of sustainability. Collapse is sometimes referred to as a plausible scenario that would be reached either by accelerated climate change (Wallace-Wells 2019), by energy depletion (Fernández Durán and González Reyes 2018b), or by the depletion of all kinds of resources required by the human species (Meadows et al. 1972).

But there are more versions. For example, in the field of materials, Valero, Valero and Calvo (2021) propose a future scenario called Thanatia, in which minerals would be homogeneously distributed throughout the earth's crust. In other words, there would no longer be "deposits" of concentrated minerals with low entropy to obtain the materials we need at a reduced cost (as is the case now). For these authors, Thanatia is not a prophecy but rather a reference scenario against which to measure, in terms of exergy, how valuable the "low entropy pile" is that we still enjoy today by being able to extract minerals that are concentrated in certain places. Humanity, with its intensive production in the use of materials for consumer goods with a very short lifetime, would be using up this pile without being aware that, at some point, it will have to invest much more resources (energy and materials!), much more "low entropy", to be able to extract these minerals that will no longer be so easily accessible.

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The collapse also admits a historical approach in two senses. On the one hand, different human societies already collapsed, as Diamond documents in his book Collapse (Diamond 2005). This is a fascinating analysis because the challenges those human groups faced, unsuccessfully, share suggestive similarities with those we face today. However, the analogy is not total because the role of technology places us in a different position from those groups that did not manage to survive. Are we guaranteed to survive because of our superior technological development compared to the human groups that collapsed in the past? Will our superior scientific-technological level, our superior capacity to increase it, or both save us if it does?

On the other hand, the concept of human collapse understood as a prediction, has a history going back at least to Malthus' predictions that an exponentially growing humanity could not feed itself on edible resources that could, at best, grow linearly. What can we learn from the history of human collapse as a prediction? Why did earlier versions fail? What, if anything, is different about the current version of the collapse prediction?

The analysis of collapse also admits a radically different discussion. Collapse would not be a hypothetical scenario of the future, the result of "entropic" constraints to which we are perhaps doomed, but a current reality for a significant part of the world's population, the result of a struggle of interests, of a political economy in which some, the dispossessed, have been losing the game for as long as there have been historical records. And all without the need for climate change to worsen or oil to run out. Worrying about future collapse would be a luxury that only the privileged part of the world's population can afford, those who are not already living it routinely. This is an exciting point of view, although the realisation that the present collapse is the everyday life for a part of the world's population does not negate the relevance of possible future collapse due to global environmental constraints. Political economy defines how the cards are dealt in society regarding opportunities, and that deal is already producing collapse situations; it has consistently produced them. However, environmental limits could impose even more restrictions on human societies as a whole, reducing the number of cards to be dealt with, which is also relevant.

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Finally, the field of collapsing knowledge also discusses the possibilities of escape from dystopia. For example, is it realistic to think of colonising other planets as a way out of the environmental dilemmas we have on our planet? It is not feasible. Leaving aside the question of who could agree to leave the EEarth (with today's technology, it is clear that only a few people could), it seems complicated for any human group to take everything they need to subsist off Earth as luggage. They would need a miniature version of the biosphere! Considering that life on Earth is a phenomenon absolutely adapted to the conditions of the planet on which it arose, transplanting those conditions to another planet does not seem possible.

Short- and medium-term questions

In the short and medium term, the relevant questions we have identified fall into three areas: analytical strategies, technical action strategies and political strategies.

In terms of analytical strategies, it is interesting to ask: what is the purpose of using the concept of collapse as a scenario now? It can be used as a reference scenario that allows a kind of measurement of a process of entropic increase, as is the case of the Thanatia scenario that has already been discussed in relation to mineral extraction (Valero, Valero, and Calvo 2021). On the other hand, Diamond uses the concept as a warning to navigators: "Beware! This can also happen to today's societies", so we should learn from our

> *There would be another type of collapse that understands collapse as indisputable but in a certain sense hopeful, since a more austere future could forcibly open up options for a more just society.*

past mistakes to avoid repeating them (Diamond 2005). Along the same lines, to mobilise social change, there would be a warning about the devastating effects of climate change that Wallace-Wells raises in his Inhospitable Planet (Wallace-Wells 2019). Finally, there would be another type of collapse (Riechmann 2022; González Reyes 2022; 2021) that understands collapse, on the one hand, as indisputable, but on the other as something in a certain sense hopeful, since a more austere future could forcibly open up options for a more just society. This approach also admits strong criticism (Santiago, 2023).

In terms of technical strategies for action, the discussion is wide-ranging. If we focus on energy, the questions are tremendous: how do we prioritise substituting fossil energy with renewable energies? Is this substitution possible when, for the moment, renewables are not really "renewable" because they still require a significant role for fossil energy (González Reyes 2022; Carpintero and Nieto 2022; Foxon 2017)? From the energy point of view, the question of degrowth also arises as something that can be modelled (Carpintero and Nieto 2022; Lallana 2022), which is debated as to whether it is inevitable (i.e., whether we will degrow by hook or by crook) (Carpintero and Nieto 2022), or whether it is the solution to the question of sustainability (Hickel 2021). From a very different position, Branco Milanovic, an economist and expert on the evolution of inequality, argues strongly about how politically unfeasible degrowth would be in a democracy (Milanovic 2021).

In terms of materials, questions arise around recycling or, if we broaden the focus, the circular economy, something that, for Valero et al. (2022), is a chimaera. To posit that, via reuse and recycling, we could have a truly circular economy, which would be to return to the fantasy of the standard economic description, in which the economy is a closed circle that can function perpetually without any external constraint. For these authors, there would be an inevitable "entropic advance" caused by the economic system in terms of the degradation of low entropy material sources. Our current society would be causing a very rapid advance with a straight trajectory. At the same time, an (illusory) perfectly circular economy would stop that advance, causing the economy not to move from its entropic level. The reality, however, could, at best, be on a spiral trajectory, where the entropic advance is undeniable but slower than it is today because recycling and reuse allow the environment not to degrade as quickly.

The two previous areas, energy and pollution, also offer an interesting dimension of combined analysis: escaping from dependence on fossil energy by developing renewable energies implies acquiring a new dependence, in this case with certain materials ("rare earths") on which the manufacture of devices such as solar panels or wind turbines is heavily dependent (Valero, Calvo, and Valero 2022). This is not to say that we should not move in this direction, but simply that we should be aware of what it implies.

The central question of how we deal with climate change and its consequences stands out in pollution. First, authors such as Lomborg (2021) argue forcefully that we should not devote too many resources to mitigating something that is already largely unavoidable. It would be very complex and costly to stop if it can be prevented.[11]

However, other authors assume that climate change is worth fighting, and then the range that opens up concerns how to achieve this and with which policies. Modelling economic growth to find out the carbon tax that would optimally reduce emissions (W. D. Nordhaus 2013; 1993; W. Nordhaus and Sztorc 2013), the discussion of policies and areas of work (International Monetary Fund 2021; 2019), the relevant macroeconomic implications of a truly determined policy to reduce emissions (Pisani-Ferry 2021), or the demands that such an approach would place on monetary policy (Daly

[11] In 2008, Lomborg argued that it did not make sense to put all efforts into halting climate change when there were more pressing (and cheaper to solve) problems already plaguing poorer countries, such as hunger or lack of access to clean water (Lomborg 2008).

2021), are just some of the most debated topics. To close the block of technical questions, it is worth mentioning an amendment to the whole: is "sustainability" of any use, or is it merely a market niche with which social movements entertain themselves and some companies gain prestige and money, but with little more than cosmetic results? (Escrivà 2023).

The third block of questions to think about in the short and medium term points to strategies for political action. If we come to understand what is happening and what needs to be done in terms of sustainability, how can we identify the policies that could be useful, which of these would be realistic, and which would be progressive? For example, indirect green taxation (carbon tax) is fiscally regressive, and there is also much debate about whether electric car subsidies make environmental sense and their effect on income distribution.

It is also interesting to ask how social forces can be brought together to support political change to avoid the worst-case collapse scenario. In this sense, is "collapsism" useful for mobilising in favour of halting environmental degradation? For Santiago (2023), the answer is that it is not. The insistence on a supposed certainty of future collapse, far from being a challenge to the prevailing system, would be almost reassuring for it, as it would imply that the environmental movement itself has assumed an approach that there is no possible alternative, so why worry, why protest?

The problems of mobilising for sustainability would go beyond collapsism. Even if collapsist despondency does not prevail, it does not seem easy to motivate society to move under the incentive of "avoiding future environmental damage". It is not a particularly exciting slogan in those terms. How to achieve a more seductive narrative is a challenge.

Imagine if we knew not only what to do and using what policies but also had the social support to turn these ideas into real policies; we are still not done with all the problems. How do you manage politically the transition to a more sustainable economy, a process that inevitably generates sectors that are objectively disadvantaged in their short-term interests (or that, at the very least, will perceive themselves as disadvantaged)? How is this section of the public to be compensated for the costs that the transition may entail, and how is it to be persuaded to support such a transition and not instead support policy options that promise to halt it or even deny the initial problems? We are already seeing such tensions today, a textbook example being the problem of access to water for agricultural use in the area surrounding the Doñana National Park in Andalusia.

Final thoughts

This paper clarifies some basic notions of physics, such as entropy and the second principle of thermodynamics, and their relevance for analysing the economic system and, in particular, sustainability. It also gives an overview of some relevant issues related to sustainability where the current debate is most active.

As noted in the introduction, the list of issues raised was not intended to be exhaustive nor to draw clear conclusions. Hopefully, some or many of the questions outlined are already answered in the abundant literature, which the writer of this text intends to explore in greater depth from now on. To undertake this work, four final ideas that emerge from all discussed and set out below may be helpful.

The first encapsulates the importance of the topic at hand. Sustainability is relevant because it addresses whether humanity will be sustainable, i.e., viable long-term. To achieve sustainability, which is currently not guaranteed, we will have to find out: (i) what the human society of the future must be like to satisfy the conditions that sustainability imposes (first: use exclusively renewable energy sources; second: not exhaust the stock of materials that the earth's geology has given us; third: not deplete the biosphere or make its sustainability unviable); and (ii) how humanity can reach that scenario alive. Both questions, each more complex than the other, remain unanswered for now.

The second idea is that the interrelationship between energy, materials and waste is inherent in the nature of the economic system, as an entropic system that enables the organisation of the satisfaction of human needs. In each of these three areas, there are actual or potential constraints to the sustainability of human society as we know it, but these constraints are not independent of each other, as there are strong channels of influence between them. So, we should reach a holistic perspective, which is essential to achieve some coherence in action for sustainability.

The third idea picks up on the previous thread: the interrelationship between energy, materials and waste is often neglected when discussing anything to do with sustainability. Most of the contributions to the understanding of sustainability and its dilemmas come from specific areas, either energy, materials or pollution in one of its versions (climate change, microplastics, other pollutants...). All these contributions are essential, but it is striking to note the scarcity of work exploring the cross implications of the different fields, which remain rather impenetrable to each other as if the connection between them were an accessory element when it seems to be a central issue. This probably limits the scope, relevance, and usefulness of the recommendations that emerge from the analyses undertaken.

The fourth and last idea concerns what to do from a methodological point of view. If the relevant sustainability issues (energy, materials and waste) are strongly interrelated, perhaps we should go for an interdisciplinarity that allows us to fill the whole map of pending issues with knowledge and connect these elements of knowledge with each other. Interdisciplinarity does not imply that everyone should analyse everything. Specialisation is necessary to make relevant contributions in any field; indeed, we need relevant contributions in all fields. But we also need to put all the pieces together.

One possibility to move in this direction is to take an example from the Intergovernmental Panel on Climate Change (IPCC), the UN's intergovernmental organisation. The IPCC has established itself as the most authoritative voice on the science of climate change, resulting from a highly choral work.

However, given the complexity and scope of the questions to be answered, we probably need an even more choral Sustainability Panel than the IPCC. All dimensions of human society are challenged by the question of sustainability, especially given the magnitude of the transformations (technological, economic, social and political) that are likely to be necessary to move towards a sustainable human society. This, coupled with the difficulty we humans have in incorporating the future into our present decision-making, means that understanding the dilemmas of sustainability from a scientific and technical point of view (no small task) is not enough.

We need to consider the social and political implications of what we are dealing with and understand how we got here (which is a function of scientific and technical, but also political, sociological, and historical factors).

We need to consider the social and political implications of what we are dealing with and understand how we got here (which is a function of scientific and technical, but also political, sociological, and historical factors). And if we do figure out what direction to take, we have to find ways to overcome the obstacles and resistances that will arise (and are already arising), as is the case in any process of social transformation.

So a panel of experts in, for example, biology, physics, chemistry, engineering and economics (fields of knowledge well represented in the IPCC), while essential, would probably not be up to the challenge. More voices from more fields will be needed: sociology, history, anthropology, philosophy, international relations... as many voices as possible, from all disciplines, with the sole condition of wanting to contribute to a constructive debate because it is foreseeably a question of changing society as we know it. The challenge seems urgent, although it is difficult to determine precisely how much. Moreover, the urgency in each dimension involved will probably differ.

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Emulating the IPCC seems a necessary first step in this direction, as it is a matter of replicating something we have already been able to create. It will then have to be improved. Of course, it does not seem a good alternative to trust that the interdisciplinary cooperation required will come naturally through the incentives offered by academia, which instead encourages hyper-specialisation in watertight compartments that are clearly separable from the rest. We need something compatible with more shared work without denying the need for specialisation.

Engaging in sustainability from biology may sound almost conventional. To do it from engineering or economics, politics, sociology or philosophy is "alternative", but to do it from physics or mathematics, history or international relations is almost extravagant. If promoting the joint work of people from all these disciplines sounds difficult, pretending that this interdisciplinary work flourishes spontaneously is directly utopian. The challenge is for it to cease to be so.

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