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ENERGY AND THE ECONOMICS OF SUSTAINABILITY. THE ENTROPY PARADOX

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ABSTRACT: This paper analyzes the concept of entropy, as understood by both the weak sustainability and strong sustainability scholars. In seeking an answer to why such an apparently rigid concept cannot be used to falsify either paradigm, we make use of recent developments in Physics, in order to further substantiate the statistical nature of both the concept of entropy, and of the Second Law of Thermodynamics. We conclude that the probabilistic nature of the concept of entropy forbids the theoretical falsification of either paradigm, and designate this situation as the 'entropy paradox'.

KEY WORDS: Weak sustainability, strong sustainability, entropy, Georgescu-Roegen.

1. INTRODUCTION

The purpose of this article is to analyse the concept of entropy, specifically, its implications for the two main sustainability paradigms in economics. We review the perspective from physics and make use of recent developments in this domain to show that entropy is a concept intimately linked to statistical predictions. Therefore, it is clear that importing such a concept into economics, and making rigid judgments based on it has its own hazards. Nevertheless, the argument made in this paper is that the debate between weak sustainability and strong sustainability followers cannot be decided in favor of one or the other, based solely on the concept of entropy and the second law of thermodynamics.

The statistical nature of the second law of thermodynamics permits both to exist, and as such, none of the said paradigms can be falsified simply by invoking the second law of thermodynamics and the concept of entropy. More over, experiments from physics are attesting the statistical nature of this law, and to that end, that, indeed, entropy can sometimes be seen to move in the opposite direction than the one postulated by the second law of thermodynamics. This peculiarity goes against the precepts of the strong sustainability paradigm and gives credence to the weak sustainability adepts, who claim that the second law of thermodynamics does not have a significant impact on economics.

Given this state of affairs, it is clear that, besides the paradigms themselves, the chasm deviding the two paradigms of sustainability warrants research in itself. While it is not the only barrier in bridging the gap between weak and strong sustainability adepts, the Second Law of Thermodynamics is clearly an important factor in this problem. As an import from physics it has an aura of scientific truth, so normally it should have quickly been picked up in Economics. The fact that it has not, and that, moreover, its influence is debated, has been a motivating factor for writing this article. The contribution to this topic lies in showing that the Second Law is not a viable reason for discarding either of the sustainability paradigms, due to its statistical nature.

2. ENTROPY[1] IN ECONOMICS

The concept of entropy has been introduced in economics by the works of Nicholas Georgescu-Roegen [1-4]. The perspective used by Georgescu-Roegen is that entropy is an 'irrevocable qualitative degradation of free into bound energy' [1]. Nowadays, however, one is more likely to come across a modern interpretation of this degradation as a continuous transformation of order into disorder. The idea is based on the observation that free energy is an ordered structure, while bound energy is a chaotic, disordered distribution [1]

Borrowed from physics, entropy is defined as 'a numerical way of measuring the grade of energy in a system' [5]. Another definition would be a measure of the degree of energy dissipation in a system, i.e. measuring the spontaneous tendency of energy to degrade and be dissipated in the environment [6]

The connection to economics, as seen by Nicholas Georgescu-Roegen is that the world is essentially finite, and, not only that, but that 'the economic process materially consists of a transformation of low entropy into high entropy, i.e. into waste, and since this transformation is irrevocable, natural resources must necessarily represent one part of the notion of economic value' [1]. Nothing is created, nothing is destroyed, and the economic process is simply a large scale low entropy transformation process.

Regardless of how we view the works of Nicholas Georgescu-Roegen (reviews have been mixed, and his ideas have been slow to permeate into mainstream economics), economists had

1Throughout this article I will sometimes refer to, or infer that, low entropy is equivalent to free energy and high entropy, the same as bound energy. While you would be hard pressed to find a physicist that would agree with this assertion, since entropy has a distinct temporal characteristic which energy lacks, for the purpose of this article, the rough equivalence can hold. Energy, like matter, cannot quantitatively change with time, since the universe is an isolated system (at least to our current knowledge). Entropy on the other hand is considered an irreversible process, with most empiric studies confirming this. Entropy is thus viewed as a qualitative process, an arrow of time, since, being an irreversible process, it clearly shows the flow of time in a given system. This however is still a debated issue in physics, as we shall see.

been introduced to the concept of entropy. As we shall see, mainstream economics dismissed the concept as being unimportant, while others embraced it as eye opening for the supposedly mistaken route economics went on. This duality carried over into the field of sustainable development, where the concept of entropy degradation and the second law of thermodynamics have been key arguments in the disputes between the two sustainability paradigms. Since no clear winner has emerged from this divergence, maybe a closer look at the peculiarities of entropy and the second law of thermodynamics needs to be had.

3. SUSTAINABILITY, A GAME OF TWO

The two main concepts that address the issue of sustainability are represented by the 'weak sustainability' and the 'strong sustainability' paradigms. Weak sustainability is derived from the works of Robert Solow [7-11] and John Hartwick [12-14], although other authors have contributed to its development [15-17]. It is also heavily influenced by the earlier and long neglected works of Harold Hotelling – from which the so-called Hotelling rule was derived [18]. Essentially, the weak sustainability adepts seek to resolve the issue of scarcity of resources by postulating substitutability between natural capital and human-made capital. It is acknowledged that natural resources will eventually run out and, since that event is unlikely to be prevented, technology is given a central place in assuring humans will successfully switch from an economy highly dependent on natural capital to one more reliant on human-made capital. This postulated technology, obviously not available at the moment, is called a 'backstop technology' [15], and the implications are profound indeed, since it is openly opined that this technology will not only facilitate a switch from an economy heavily reliant on natural capital to one dependent on human-made capital, but that this human-made capital, which will constitute the backbone of the new economy, will be virtually ubiquitous. Thus, the problem of scarcity of resources will be one condemned to the books on the history of economic thought. An equally essential property of this paradigm is that welfare must be equal between generations. In other words, and based on the Rawlsian maximin criterion, on a long term scale, no generation can be worse off that any of its predecessors or successors. There is no sacrificed generation in order for others to prosper, which implies that welfare is evenly distributed in time.

The other paradigm to note is the 'strong sustainability' perspective, based mainly on the works of Herman Daly [19-24]. As with the other paradigm, others have contributed to this view [25-29], and maybe as a consequence, this paradigm is rather more diffuse intellectually, in the sense that strong sustainability encompasses a broader side of economics, compared to the weak sustainability perspective. It is also true that, given this approach, 'strong sustainability' can be seen as a superior paradigm, in the sense of Kuhn [30]. The basic assertion is that at least some parts of natural capital are not substitutable by human-made capital (critical natural capital), and as such, at least parts of our natural capital need to be preserved. This preservation means not consuming more than the environment can supply (maintaining the source side viable) and not disposing more wastes in the environment than it can manage to absorb (maintaining the sink side viable). In other words, take as much out of the environment as possible, without ever depleting the stocks, and throw just enough wastes back into the environment as not to surpass the normal recycling capacity of the natural environment. A steady-state economy, as called by the strong sustainability adepts [19]. As mentioned, strong sustainability addresses more issues than weak sustainability (like income taxes, pollution taxes, economic growth, population size, technological progress, etc.), but for the purpose of this article we will be dealing with the limited substitutability assertion. It is worth mentioning at this point that the works of Nicholas Georgescu-Roegen are fundamental to the strong sustainability doctrine. Thus, the second law of thermodynamics plays a central role in this paradigm and is also one of the key arguments used against the weak sustainability view.

Both these paradigms tackled the problem of entropy, albeit with clearly different attitudes and results. As asserted by Robert Solow, quoted by Herman Daly, '[...] everything is subject to the entropy law, but this is of no immediate practical importance for modeling what is, after all, a brief instant of time in a small corner of the universe' [31]. Solow himself acknowledges the effect of the second law of thermodynamics on the economic process, by stating that '[...] the laws of thermodynamics and life guarantee that we will never recover a whole pound of secondary copper from a pound of primary copper in use, or a whole pound of tertiary copper from a pound of secondary copper in use. There is leakage at every round […] There is always less ultimate copper use left than there was last year, less by the amount dissipated beyond recovery during the year' [8].

On the other side, Herman Daly has often based his arguments against mainstream economics and 'growth mania' on the second law of thermodynamics [22]. 'Consider an hour glass. It is a closed system in that no sand enters the glass, and none leaves. The amount of sand in the glass is constant; no sand is created or destroyed within the hour glass. This is the analog of the first law of thermodynamics: there is no creation or destruction of matter-energy. Although the quantity of sand in the hour glass is constant, the qualitative distribution is constantly changing: the bottom chamber is filling up and the top chamber becoming empty. This is analog of the second law, that entropy (bottom-chamber sand) always increases. Sand in the top chamber (low entropy) is capable of doing work by falling, like water at the top of a waterfall. Sand in the bottom-chamber (high entropy) has spent its capacity to do work' [26]; the analogy was first put forward by Nicholas Georgescu-Roegen. In another paper, Daly says: 'But the facts are plain and uncontestable: the biosphere is finite, nongrowing, closed (except for the constant input of solar energy), and constrained by the laws of thermodynamics. Any subsystem, such as the economy, must at some point cease growing and adapt itself to a dynamic equilibrium, something like a steady state' [22].

Although more citations could clearly be found, it seems obvious that the concept of entropy and its relevance towards the economic processes that take place in society is viewed differently by the two paradigms. None deny its existence; however one places a great deal of importance on it, while the other brushes it away as irrelevant. Since we are dealing with a concept from physics, we should wonder: why is this situation perpetuating?

4. THE ENTROPY PARADOX

So we have a concept, entropy, which seems to dictate the course of energy flow, following a very strict pattern, given by the second law of thermodynamics. Given the fact that both sustainability paradigms acknowledge the existence of the entropic process in economics (although the effect differs in intensity depending on which paradigms views it), it would seem illogic for this duality to exist. If the second law of thermodynamics tells us clearly that entropy is continually transformed from a low state, of free energy and ordered structures, to a high state, of bound energy and chaotic structures, with or without the involvement of human beings, we must wonder: how does this situation reconcile with the postulations of the two sustainability paradigms? At first glance, it would seem that the second law of thermodynamics contradicts the assertions of the weak sustainability paradigm. If this law tells us that energy is continually being qualitatively changed from a free state, towards a bound state, it would seem that humanity is doomed to linger in a world of ever decreasing available energy. Since high entropy is being continually churned out by the human processes, how can we expect to reach a place in space and time where our energy problems are essentially a thing of the past, as claimed by weak sustainability scholars? The mass-energy conservation law tells us that the energy of a system does not decrease, but at the same time, we know that free energy is being converted to bound energy and thus rendered unavailable to humans.

On the other hand, this view from physics seems to fit the strong sustainability paradigm like a glove. Indeed, one of the basic assumptions of this paradigm is that the world around us is essentially finite [22; 24], and as such some preservation is required, both on the source and on the sink side. As I will claim further, this should be interpreted in the sense that the strong sustainability is more realistic; it relies more on things we already know, whereas the weak sustainability is basing its model on assumptions (which might happen, none the less).

One such assumption is that, at a certain point in time and space, technology will give us the necessary tools for substituting natural capital for human-made capital. There is an intrinsic particularity to the entropy concept, which most other notions from physics lack. That is a statistical side, which gives entropy a certain conceptual vagueness. Unlike other laws of physics, which are more rigid, the second law of thermodynamics allows for the situation opposite of its postulation to occur. In other words, high entropy can theoretically become low again, and this is possible and non-contradictory because the second law of thermodynamics is a statistical one. The implications from this peculiarity are quite interesting. On a large time-scale, the entropy can be seen to move in the other direction, opposite to what the second law of thermodynamics tells us; it is by no means impossible, just unlikely, and the fact that we are currently seeing low entropy being transformed into high entropy might be just a sign that we have not studied this effect long enough.

This is where the entropy paradox comes into play. It lends credence not only to the weak sustainability paradigm, but also to the strong sustainability perspective. On the one side, one clear deduction from the physics thermodynamic model is that the resources of the world are finite. If low entropy designates the resources that we can successfully harness in order to fuel our societies, and if we know that low entropy is continually being transformed into useless high entropy, such that the overall entropy of a system is always increasing (not in a quantitative sense), then it makes sense to postulate that scarcity of resources is a real situation, and thus the resources we live off are finite. This clearly supports the strong sustainability paradigm.

On the other hand, the concept of entropy and even more-so, the interpretation it is given by statistical thermodynamics tells us that on a large time-scale, the conversion of high entropy into low entropy might not be as impossible as we think. These are all interesting assertions, because they allow, at least on an unlikely, theoretical level, the possibility that at some point in the future, humanity will find the necessary means to reintegrate bound energy into the energy consumption circuit. Since technological progress is, presumably, one way of reaching that level, the weak sustainability paradigm suddenly becomes plausible.

Therefore, in a strange way, the concept of entropy seems to validate both sides of the debate. True in keeping with tradition, the interpretation given to entropy from the strong sustainability side is much more firmly ground in reality, while the weak sustainability bases its ideas on a more future-oriented perspective on entropy.

5. MORE ON THE STATISTICAL SIDE OF THE SECOND LAW OF THERMODYNAMICS

Let us recollect that the probabilistic laws of statistical thermodynamics do not explicitly deny the possibility of a reversal of the laws of thermodynamics. Just as a practical example of the nature of the entropy concept in physics, we can relate to recent research in this field. In the mid nineties, the Fluctuation Theorem was put forward, and it seeks to give a more accurate mathematical explanation for the entropy flow in a given system [32-35]. Without going into detail, since that is not the purpose of this article, the said theorem gives a mathematical expression for the probability that entropy will increase or decrease. It proves that 'in large systems observed for long periods of time, the Second Law is overwhelmingly likely to be valid. The Fluctuation Theorem quantifies the probability of observing Second Law violations in small systems observed for a short time' [35]. Indeed, in the wake of such theoretical considerations, empirical studies soon followed [36-37], and these studies showed precisely that during limited time periods and at micro scales, entropy can be observed to move in a way inverse to the postulation of the second law of thermodynamics.

One way of mathematically introducing the Evans-Searles fluctuation theorem is [38]:

$$\frac{p(\Omega_t = A)}{p(\Omega_t = -A)} = \exp(A) \tag{1}$$

where $p(\Omega_t=\pm A)$ is the probability that the dissipation function Ω_t (t is time) will take on arbitrary values A and -A, respectively.

As explained by the original authors, '[the fluctuation theorem] is an expression that describes the asymmetry in the distribution of Ω_t over a particular ensemble of trajectories […] any trajectory of the system that is characterised by a particular value $\Omega_t=A$ has, under time-reversible mechanics, a conjugate or time reversed anti-trajectory' with $\Omega_t=-A$. In this way, the LHS of the FT[2] has also been interpreted as a ratio of the probabilities of observing trajectories to their respective anti-trajectories' [38]. In profane terms, the above expression is a mathematical construct for the ratio of probabilities that entropy will move as predicted by the second law of thermodynamics ($\Omega_t=A$), or opposite of it ($\Omega_t=-A$).

2 Original abbreviations: LHS = Left Hand Side (of the equation), FT = Fluctuation Theorem.

The physics behind the above mentioned formula are beyond the purpose of this paper. What is important for economists is that the mentioned formula provides a clear (and recent) description of the statistical side of the second law of thermodynamics. While it is true that the second law of thermodynamics holds at the macro level, recent research has proved that over short time periods, and at the micro level, the entropic process can be seen to go in reverse.

It is, therefore not enough to try to dismiss an entire sustainability paradigm, based solely on a **statistical** physics law. When rebuking weak sustainability, many economists make the mistake of pointing towards the second law of thermodynamics, to make their point of inexorable entropy increase. While it is true that the said law holds (at least to my present knowledge) at macro scales, and only falls short at the micro level, generalizing the predictions of a statistical law is a slight exaggeration, one with which at least some physicists would object.

6. CONCLUSIONS

Statistical thermodynamics, true to its name, works with probabilities and the results make up predictions. Therefore, although the second law of thermodynamics seems to support the paradigm of strong sustainability, it does not specifically deny the postulations of the weak sustainability view. In this sense, it is the very nature of the concept of entropy, as we understand it today that leaves enough blank spaces in our understanding of the natural world, so that both paradigms can coexist. The problem of sustainability and entropy in economics raises issues because the second law of thermodynamics is a statistical one, therefore the concept of entropy is inextricably tied to probabilities. Thus, elaborating a paradigm of sustainability on the statistical variations of a concept makes setting future goals a haphazard issue.

Given the said things, it becomes clear that the two sustainability paradigms are not mutually exclusive, at least not stemming from the concept of entropy, as it is believed, mainly by strong sustainability adepts (e.g. Herman Daly). While it is true that the concept of entropy and the second law of thermodynamics play a central role in this paradigm, this fact alone is not enough to falsify the paradigm of weak sustainability. Although it is recognized that the latter paradigm is more 'optimistic' in its predictions, and thus relies more heavily on future events that are at best uncertain, the concepts from physics used by some strong sustainability scholars are not enough to render the mainstream paradigm false [39]. The contributions from thermodynamics might be important for economics; however, with regards to the particular problem of sustainability and the two 'opposing' paradigms, they are not enough to falsify either view.

The second law of thermodynamics is indeed statistical in nature; therefore not any one paradigm of sustainability can successfully be falsified by asserting the second law of thermodynamics as a key argument. It might be argued that, due to the overwhelmingly high chances of a large system (observed also over a large time interval) proceeding in accord with the second law of thermodynamics, there are equally high chances to dismiss the weak sustainability, basing one's arguments on the laws of thermodynamics. As one could tell though, there is clearly a statistical component in the fore mentioned argument; therefore the weak sustainability paradigm cannot be dismantled on the basis of a probabilistic law, which has empirically been shown to admit reverse events.

That is what I chose to designate as the 'entropy paradox': none of the two main sustainability paradigms (weak and strong) can be falsified at this time, by asserting the second law of thermodynamics. It is in accord with the postulations of the strong sustainability paradigm, in that the world is essentially finite, but it does not refute the precepts of weak sustainability, due to intrinsic statistical nature of the concept of entropy.

Eric Neumayer is, in my opinion, correct in saying that both paradigms are non-falsifiable [30], although the reasons put forward by Neumayer are different than mine. Other views, such as those put forward by Bryan Norton [40] might be valid none the less, since the differences between the two paradigms are indeed quite large. It is possible that the valuation of natural environment, for example, is one of those methodological issues preventing the settling of the issue. It would however be an exaggeration to establish that there is no shared conceptual basis, no shared assumptions, no consensually accepted methodology and no common scope between the two paradigms.

Extra-paradigmatic quarreling might play a certain role in this dispute, but these differences might, to a certain point, also be attributable to misused concepts, imported from other disciplines. The 'entropy paradox' is simply just one more brick in the wall separating the two paradigms, but at the same time, forbidding the falsification of either one.

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