Thermodynamics

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Abstract

During the 19th century physics underwent a revolution. Sadi Carnot, Lord Kelvin, Rudolf Clausius and others founded a new field of physics, thermodynamics, which focuses on the study of energy.

Although energy is one of the most important economic production factors, thermodynamics does not play a key role in Mainstream Economics. However, energy is necessary for every production process and has an impact on nature because it creates environmental damage. Its use leads to irreversible loss of coal, oil and gas. This is the reason why the founder of Ecological Economics Nicholas Georgescu-Roegen focused on thermodynamic considerations in his pioneering work *The Entropy Law and the Economic Process* (1972).

This concept explains the consequences of the two fundamental laws of thermodynamics: (i) Energy can neither be created nor destroyed, but only transformed. (ii) To give an example of the second law: Heat will by itself always transfer from a hotter to a colder body, like a heated stone will give up its heat to the cooler air surrounding it.

This concept lays the foundation for an understanding that every industrial production process yields joint products, at least one of which is a waste product. This fact is easily communicated to the public, heightening awareness of the danger of our mode of production.

A practical example is the production of steel by using coke and iron ore. The output is not only steel but also the remains of the manufacturing process, such as CO2, waste water, dust etc.

Related concepts: JOINT PRODUCTION; SUSTAINABILITY & JUSTICE; IRREVERSIBILITY; TIME; EVOLUTION

1. History

Classical mechanics deals with systems with few elements, e.g. a stone falling to the ground or the movement of the planetary system. It is possible to completely describe and know these systems with few measurements. Moreover, all the behaviour of these classical mechanical systems is reversible in time. The laws of quantum mechanics are valid in this kind of world. Temperature and entropy have no place here. We call these systems micro-systems. In contrast, macro-systems, e.g. a pot of water, have many, even often very many, systems. The complexity of these macroscopic systems is very great, e.g. a balloon with one mol of gas contains about 10^{23} interactive particles; hence it is practically impossible to completely know the state of a macroscopic system. Therefore, it is advisable to restrict oneself to few global observables, such as temperature and pressure, which do not make sense in a micro system. Different physical laws hold for these macro systems. For example, we shall show below that so-called arrows of time [see concept IRREVERSIBILITY] characterise these systems. One variable is of special importance, namely the notion of entropy, unknown until it was discovered by Rudolph Clausius (1822 –1888) in 1865.

The general study of macro systems is the subject of the field of thermodynamics. Its origins lie in the first half of "the 19th century when practitioners, engineers and scientists like James Watt (1736 – 1819), Sadi Carnot (1796 – 1832), James Prescott Joule (1818 – 1889), Rudolph Clausius (1822 – 1888) and William Thompson (the later Lord Kelvin, 1824 – 1907) wanted to understand and increase the efficiency of steam at which steam engines, i.e. macro systems, perform useful mechanical work. From the beginning, this endeavour has combined the study of natural systems and the study of engineered systems – created and managed by purposeful human action – in a very particular way, which is rather unusual for a traditional science such as physics" (Baumgärtner 2004: 103).

It was the great economist, the Rumanian Nicolas Georgescu-Roegen (1906 – 1994), who showed in his pioneering study *The Entropy Law and the Economic Process* (1971: 3) how Thermodynamics can establish the conceptual foundations of Ecological Economics: "The significant fact for the economist is that the new science of thermodynamics began as a physics of economic value and, basically can still be regarded as such. The Entropy Law [i.e. the Second Law of Thermodynamics; the author] itself emerges as the most economic in nature of all natural laws." This insight led him to demand a radically new beginning of the conceptual foundations of Economics. Georgescu-Roegen is one of the main founders of Ecological Economics.

2. Theory

First, we give a brief overview for the hurried reader (Section 2.1) and only thereafter turn to a general introduction (Section 2.2). To understand the first two Laws of Thermodynamics, it is helpful to know their historical framework (Section 2.3). Since the concept of entropy is so difficult to understand, we offer an additional way to present it. To this end we turn to statistical mechanics (Section 2.4). Entropy was first associated mainly with heat, which happened in phenomenological thermodynamics. The latter's difference to statistical mechanics is described in Section 2.2. Some indications as to the relationship between entropy and information theory are given in Section 2.6.

2.1 A brief overview for the hurried reader

"Thermodynamics is the study of heat and energy. At its heart are two laws that describe how energy moves around within a system, whether an atom, a hurricane or a black hole. The first law describes how energy cannot be created or destroyed, merely transformed from one kind to another. The second law, however, is probably better known and even more profound because it describes the limits of what the universe can do. This law is about inefficiency, degeneration and decay. It tells us all we do is inherently wasteful and that there are irreversible processes in the universe. It gives us an arrow for time and tells us that our universe has an inescapably bleak, desolate fate.

Despite these somewhat deflating ideas, the ideas of thermodynamics were formulated in a time of great technological optimism – the Industrial Revolution. In the mid-19th century, physicists and engineers were building steam engines to mechanise work and transport and were trying to work out how to make them more powerful and efficient.

Many scientists and engineers – including Rudolf Clausius, James Joule and Lord Kelvin – contributed to the development of thermodynamics, but the father of the discipline was the French physicist Sadi Carnot. In 1824 he published *Reflections on the Motive Power of Fire* which laid down the basic principles, gleaned from observations of how energy moved around engines and how wasted heat and useful work were related" (Iha 2013).

2.2 Introduction

To get a feeling for the difficulty of understanding Thermodynamics, the following insight from one of the great physicists of the first half of the 20th century Arnold Sommerfeld (1861 – 1951) may be helpful: “Thermodynamics is a curious subject. The first time one engages oneself with it, one does not understand anything of it. The second time one works it over, one thinks one understands everything except for one or two small details. The third time one works through it, one notices that one does not understand anything at all, but in the meantime, one has got so used to it that one does not bother about it anymore” (Wie-sagt-man-noch-Website, last access: 16.10.2018, our translation).

Why do we deal so extensively with such a difficult subject? The reason is that thermodynamics offers new perspectives for the understanding of economic activity and the origins of environmental problems, be it depletion of natural resources or environmental pollution. The two laws of thermodynamics are of utmost importance. By the way, this statement does not hold only for this purpose but also for a much wider context. How important the Second Law of Thermodynamics is was emphasized by one of the greatest physicists of the first half of the 20th century, Arthur S. Eddington (1882 – 1944), the inventor of the light bulb:

“The law that entropy always increases holds, I think, the supreme position among the laws of Nature. If someone points out to you that your pet theory of the universe is in disagreement with Maxwell’s equations – then so much the worse for Maxwell’s equations. If it is found to be contradicted by observation – well, these experimentalists do bungle things sometimes. But if your theory is found to be against the Second Law of Thermodynamics, I can give you no hope; there is nothing for it but to collapse in deepest humiliation” (Goodreads-Webiste, last access: 16.10.2018).

For Ecological Economists it is expedient to notice that the two laws of thermodynamics lead us to recognise that the human economy is an open subsystem embedded in the larger, but finite, system of the natural environment (Boulding 1966, Georgescu-Roegen 1971, Daly 1977, Ayres 1978, Faber et al. 1995 [1983], Baumgärtner et. al. 2006 and many more).

“Why is joint production such a ubiquitous phenomenon and useful notion in ecological economics? We believe that this is because joint production is intimately related to the laws of thermodynamics. The application of thermodynamics is widely recognised as an essential element in much current ecological-economic thought, since it gives rich insights into the nature of economy-environment interactions” (Baumgärtner et al. 1995: 2).

2.3 Historical framework of the First and Second Law of Thermodynamics

How did the central concept of thermodynamics, entropy, and related questions develop since the beginning of the 19th century? “They developed thanks to a fruitful interplay of different disciplines, namely, thermodynamics, analytical mechanics, statistical physics, and communication theory.

The science of thermodynamics was initiated by engineers who wanted to understand heat engines, machines built to transform heat into mechanical work, such as the steam engine developed by James Watt in 1765. During the 18th century, scientists had recognised heat as being ‘quantitative’. They had distinguished it from temperature which measures the ‘intensity’ of the heat. It was Sadi Carnot (1796 – 1832), a French engineer, who in 1824 first analysed how heat could be transformed into mechanical work by the means of the so-called heat engine. Carnot compared this heat engine to the water wheel of a mill: As water is capable of producing work when it flows from high to low elevation, so can heat produce work when it ‘flows’ from high to low temperature in a heat engine. He also realised that the amount of potential work heat could produce is independent of the material which serves to transport heat; it depends only on the respective temperatures of the bodies between which the heat transport takes place.

The first implicit recognition of the Entropy Law

Carnot’s statement about the maximum yield, the efficiency, of thermal engines functioning between two heat reservoirs at different temperatures has many important technical implications. It can be viewed as the first explicit formulation of what we today call the ‘Entropy Law’, i.e. the Second Law of Thermodynamics, although the notion of entropy was coined 30 years later.

It took that long to fully understand the meaning of this fundamental law because it was first necessary to recognise the equivalence between mechanical work and heat, which are both different forms of energy. Carnot himself understood between 1825 and 1832 that the quantity which was conserved in the transformation process was not heat, as he had thought until 1824, but energy.

The First Law of Thermodynamics

Unfortunately, his idea was not published until after 1878, more than 30 years after other scientists had published their experimental and theoretical results, which showed a quantitative equivalence of work and heat. These results established the principle of conservation of energy, the First Law of Thermodynamics, which states that energy can neither be created nor destroyed, but can appear in different forms, such as heat, chemical energy, electrical energy, potential energy, kinetic energy, work etc. In a closed system, the sum of energies in their particular forms does not change with time.

According to this insight into transformation processes, only the form in which energy appears changes, while its total amount is conserved. Consider, for example, a freshly filled fireplace in a hermetically sealed room. After the wood has been burnt, the energy available in the form of chemically bound energy has been transformed into heat, causing a higher room temperature. The energy of the fireplace has thus been reduced by the same quantity by which the energy of the air has increased. The total energy has changed its form from chemical energy to heat energy.

Entropy Law of Thermodynamics: the Second Law of Thermodynamics

In view of the First Law, Carnot's ideas about heat engines appeared in a new light. In 1848, William Thompson, the later Lord Kelvin, introduced the notion of absolute temperature. This made it possible to give a simple expression for the efficiency of reversible engines. Kelvin (1852) also noted that it is impossible to construct a perpetual motion machine, which would produce work in a closed cycle, taking heat from a single source at uniform temperature. That means there is a fundamental asymmetry between work and heat: work (and all other forms of energy except heat) can always be completely be transformed into heat, whereas the transformation of heat into work is only possible under very specific conditions and, in addition, *always* results in the wasting of a certain amount of heat which cannot be transformed into mechanical work. Work, therefore, can be considered more useful than heat since it can directly be exploited to derive mechanical machines. In contrast, energy in the form of heat has first to be transformed into work, inevitably giving rise to the wasting of a certain amount of heat, as mentioned above. More generally speaking, in any energy transforming process the quality of energy is somewhat downgraded from 'more useful' to 'less useful'. It was this insight which established what was called the Entropy Law of Thermodynamics. Hence, the numbering of the laws of thermodynamics is logical and not temporal in order, because it neglects the fact that Carnot's formulation of the very same fact was actually made before the formulation of the principle of conservation of energy, i.e. the First Law.

Analytical formulation of the Second Law of Thermodynamics

Up to the middle of the nineteenth century, the Second Law was still a rather intuitive and therefore vague formulation of empirical facts about energy transformation processes. In 1854, Rudolph Clausius (1822 – 1888) made a decisive step to come to represent it analytically: He formally defined what he termed ‘equivalence value’, later to become ‘entropy’. The inspiration for this idea came from a formal representation of the First Law given by J. Willard Gibbs (1839 – 1903). He knew that energy can neither be created nor destroyed. Yet the energy of a particular sub-system can change. Gibbs realised that infinitely small changes of energy ($\mathrm{d}U$) can formally be represented by a product of some ‘intensive’ variable of the system and an infinitely small change of the corresponding ‘extensive’ variable:

$\mathrm{d}U$ = (intensive variable) x (extensive variable).

Intensive variables of the system are quantities which do not change when two identical systems are coupled. In contrast, extensive variables are quantities whose value for the total system is simply the sum of the values of this quantity in both systems. For example, temperature and pressure are intensive variables, volume and particle number are extensive variables. Using p to denote pressure and V for volume, a change of the system’s energy could thus be represented by:

$\mathrm{d}U = p \text{ x } \mathrm{d}V.$

Gibbs’ claim was that the change of the system’s energy could generally be represented as sum over all possible variations of extensive variables multiplied by their corresponding intensive variables:

$\mathrm{d}U = \sum \text{ x } \mathrm{d}Y_i$ with $X_i = U / Y_i$.

This equation is called Gibbs’ Fundamental Equation. Here X_i represents the intensive variable and Y_i represents the extensive variables. For all the intensive variables being used at the time, the corresponding extensive variables were well known, with one exception. There was no extensive variable corresponding to the intensive quantity temperature, T. Clausius’ response was to define the variable S through the relationship $Q = T \text{ x } \mathrm{d}S$. Here Q is the heat and S is the extensive variable corresponding to the absolute temperature T. He further showed that the variable S is a function of the system; it remains constant in any reversible cycle process, and it increases otherwise. He gave it the name ‘entropy’ (Clausius 1865); this name was based on the Greek word (*tropy*) for transformation by analogy with the name ‘energy’. Now Clausius’ formulation of the Second Law is that in an isolated system entropy always increases or, in reversible processes, remains constant. This implies, given the definition of the entropy variables, that the spontaneous exchanges of heat between two bodies can only take place in one direction, from hot to cold, in line with experience.

Isolated, closed, and open systems

At this point, two terms in Clausius' statement need further explanation. These are the terms 'isolated' and 'closed' systems. A thermodynamic system is defined by specifying a spatial boundary around some objects (which may be involved in interactions or 'processes') with respect to the potential exchange of energy and matter between the inside and the outside; Physicists distinguish between *isolated*, *closed* and *open* systems:

Isolated systems exchange neither energy nor matter with their surrounding environment.

Closed systems exchange energy, but not matter, with their surrounding environment.

Open systems exchange both energy and matter with their surrounding environment.

Whenever we use the word 'system', we refer to such thermodynamic definition. Whether truly isolated natural systems exist at all is an open question. Real systems on the earth always exchange at least energy with their environment, albeit only in small amounts. The universe as a whole could be an isolated system, but that conjecture is beyond testing, however. Let us suppose, for the sake of this discussion, that the universe is an isolated system (for more details see footnote 5 of Baumgärtner et al. 1995)" (Baumgärtner et al. 1995: 2-6).

Phenomenological thermodynamics

Today there are several branches of thermodynamics, e.g. statistical thermodynamics will be dealt with in the next Section. Up to 1870 only actual phenomena of heat energy were studied and analysed, only at the macroscopic and not on the microscopic level. After 1870 researchers examined atomic and molecular details at the microscopic level, in particular with statistical methods. To distinguish these different approaches, the pre-1870 findings are summarised under the notion of phenomenological thermodynamics, dealing with all the notions, results and interdependencies mentioned above.

Having dealt with the macroscopic level, we now turn to microscopic procedures developed after 1870.

2.4 Attempting to understand the abstract notion of entropy: statistical mechanics

A central, perhaps even the central aspect of the Second Law is that it implies the irreversibility of the evolution of macroscopic systems [IRREVERSIBILITY, EVOLUTION]. This circumstance can be seen from empirical observations in everyday experience, e.g. when burning a piece of wood or the birth, living, dying and death of a creature. "Yet the notion of entropy and the Second Law of Thermodynamics still remained rather mysterious. This is owing to the fact that Clausius' definition of entropy is rather abstract and left entropy as a variable which, at first sight, has nothing to do with irreversibility. Further, phenomenological thermodynamics, with which we have dealt up to now, does not explicitly deal with time. For that reason, temporal irreversibility is hard to grasp in the framework of equilibrium thermodynamics. The relationship between entropy and irreversibility became somewhat clearer, at least as far as the physics of gases was concerned, thanks to Ludwig Boltzmann (1844 – 1906). He gave a mechanical interpretation for entropy which enabled him to explain why it always increases with time (see for extensive explanations Faber et al. 1995: Sections 3.3 and 3.7).

Introducing statistical mechanics

Statistical mechanics, developed by James Clerc Maxwell (1831 – 1879) starting in 1860, views gases as assemblies of mol, described by probability distribution functions depending on the position and velocity of the molecules. This view allowed the establishment of the connections between the thermodynamic variables, that are the macroscopic properties such as temperature or pressure, and the microscopic behaviour of the individual molecules of the system, which was described by statistical means. In 1877, Boltzmann made the decisive step by introducing the concept of microstates and macrostates of a system. The microstate is an exact specification of the positions and velocities of all individual particles; the macrostate is a specification of the whole system" (see Baumgärtner et al. 1995: 6; Faber et al. 2002: 100).

Phenomenological thermodynamics and macroeconomics – statistical mechanics and microeconomics

The economic readers will have noted that there is a close analogy between this approach in physics and economics. Phenomenological thermodynamics corresponds to macroeconomics because it attempts to describe complex systems with few variables on the macro-level, while Statistical mechanics corresponds to microeconomics trying to cope with all possible states of a system on the micro-level” (Baumgärtner et al. 1995: 6-8).

Explaining the concept of microstates and macrostates

Let as us consider “a container which we conceive as being split into halves containing four balls which are indistinguishable. For the sake of the theoretical treatment, we number them from 1 to 4. We observe a certain number of balls in one half of the system. These different observable states are the macrostates of the system. The microstate of the system is defined by the specification of that exact configuration that specifies which ball is found in what part of the container. For example, one microstate could be: Balls 1 and 2 can be in one half and 3 and 4 in the other half of the container.

The container can be in five different macrostates: (4-0), (3-1), (2-2), (1-3) and (2-2). We note that the macrostate (4-0) can be realised by only one microstate; the macrostate (3-1) can be realised by four microstates, and finally the macrostate (2-2) can be realised by six different microstates.

Boltzmann assumed that all microstates have the same probability of occurring, provided that there is no physical condition which would favour one configuration over the other. By counting the number of different microstates realising the same macrostate, he posited that the macroscopic thermal equilibrium is the most probable state, in the sense that it is the macrostate which is realised by the largest number of different microstates. The larger the number of particles a system contains, the more likely it is to find the system in its most probable state. In our example of the container with four balls, we would thus be most likely to find the container to be in the macrostate (2-2), with an equal number of balls in each half.

Entropy as a measure of likelihood

Boltzmann related the quantity W, counting the number of possible microstates realising one macrostate, to the thermodynamic entropy S of that macrostate, by

$S = k \log W,$

where k is Boltzmann’s constant. Entropy has thus become a measure of likelihood: Highly probable macrostates, that is macrostates that can be realised by a large number of microstates, also have high entropy. The irreversibility stated by the Second Law in Claudius’ formulation (in any isolated system entropy always increases or remains constant) now appears as the almost intuitive insight that any given system always evolves from a less probable to a more probable state, where *W* and *S* are larger" (Baumgärtner et al. 1995: 7-8; Faber et al. 1995: 100-101).

"Thus, Boltzmann showed that entropy described the degree of order of a system: The lower the entropy, the higher the order; the higher the entropy, the more chaotic the system" (Baumgärtner et al. 1995: 6-8).

2.5 Phenomenological thermodynamics vs. statistical mechanics

"It should be stressed; however, that Boltzmann's statistical mechanical notion of entropy is not truly equivalent to the notions of thermodynamic entropy in the sense of Carnot, Kelvin and Clausius, although such an equivalence is often maintained even in many physics textbooks. In the latter's formulation, the Second Law of Thermodynamics is an absolute law of nature: In any isolated system, entropy always increases or remains constant, it never decreases. For Boltzmann, however, this is only a question of probability: It is highly probable that the entropy of an isolated system increases. It could, however, with very low probability also decrease. As mentioned above, the larger the number of particles a system contains, the higher the probability of finding the system in the macrostate of maximum entropy. Hence, strictly speaking, statistical mechanics supports the Second Law of Thermodynamics only at the limit of large numbers.

In phenomenological thermodynamics, the entropy concept was always intimately connected with heat. It is the merit of statistical mechanics, despite its shortcomings mentioned above, to de-couple these two concepts and show the more general nature of entropy, namely as a measure of likelihood or, equivalently, a measure of disorder. For instance, the mixing of two distinguishable gases at the same temperature and with the same density is not affected by any thermal effect, but nevertheless it leads to an increase in entropy. The concept of mixtures/disorder later on replaced the idea of heat transfer in understanding the meaning of entropy and served as a guide in generalising the entropy concept and transferring it to other disciplines, such as information theory (Shannon and Weaver 1949) and Mainstream Economics in general and Ecological economics in particular" (Baumgärtner et al. 1995: 8-9; Faber et al. 2002: 102). We will show this in the following.

2.6 Entropy and information theory

“Another approach to the notion of entropy that is totally different from the presentation chosen up to now relies on information theory. In this approach, which goes back to Claude Shannon (1916 – 2001) (1948), entropy is a measure of the information contained in a message. Since in the following we shall not refer to the resulting interpretation of entropy, we shall not here take a closer look at the information-theoretic interpretation of the notion of entropy (see Georgescu-Roegen 1971, Appendix B: 338-406, who discusses the relationship between ignorance, information, and entropy). Suffice it to note that the thermodynamic interpretation of entropy can be derived from the information-theoretic interpretation of entropy (cf. Stumpf and Rieckers 1976, Proops 1985)” (Faber et al 1995: 97).

3. Practice

It is evident from our presentation above that entropy is a difficult concept to apply. For this reason, we start with a warning (Section 3.1) and then turn to the pioneering way in which Georgescu-Roegen applied the entropy concept to analyse the economic process (Section 3.2). This leads us to the way thermodynamic insights are used in Ecological Economics (Section 3.3). We then offer the notion of joint production [JOINT PRODUCTION] as a relatively easy-to-use and easy-to-understand concept to capture essential thermodynamic constraints (Section 3.4).

3.1 A frequently overlooked warning

The entropy notion is extremely complex. Thus, the Nobel Laureate in Economics Tjalling Koopmans (1910 – 1986) (1973: 13), a physicist by training and whose first two publications were in physics, notes that ‘entropy’ is a more difficult concept than anything economics has to offer.

The physical concept is generally judged to be quite intricate. If we take the word of some specialists, not even all physicists have a perfectly clear understanding of what the concept exactly means. Its technical details are, indeed, overwhelming. And even a dictionary definition suffices to turn one’s intellectual curiosity away. It is therefore no surprise that the application of the entropy concept has given rise not only to many misunderstandings and controversies in Mainstream Economics and Ecological Economics, but often entropy has also been applied incorrectly in social contexts. One reason for this is that one needs a strong background in physics and economics to understand and appreciate the literature on this topic. Here we can only give some indications. For more details we recommend the reader read Baumgärtner et al. (1995) and Faber et al. (2002: chapter 7) which clarifies the use of the entropy concept by surveying the relevant literature. There it is shown which usages are correct and which are mistaken, which application is sensible, and which is not. The survey "act[s] as guide for the newcomer to this field. One of the main messages will turn out to be that understanding the entropy notion is to understand what is possible in Economics and what is not. Thermodynamics can show the outer limits of what is physically and economically possible:

'[T]he second law of thermodynamics tells us nothing about what will happen, but only about what cannot happen. Any claim that the second law helps us know what will happen must be scrutinised with great care' (Dyke 1994: 208).

Thus, the restrictions of the way we live in our world will be become more apparent. Further, this quotation contains an important but often overlooked warning: We cannot expect entropy to be of much use in finding explicit solutions to concrete problems. Rather, because of its very general and unifying nature it contributes to the biophysical foundations of economics as large and Ecological Economics in particular. By 'biophysical' we mean physical and biological aspects of nature which are relevant for Economics" (Baumgärtner et al. 1995a: 1-2; Faber et al. 2002: 115-116).

3.2 Georgescu-Roegens's contribution

Nicholas Georgescu-Roegen (hereafter 'G-R') (1906-1996) was the first to introduce in his seminal study The Entropy Law and the Economic Process (1971) "the entropy concept into economics in a visionary way. The economic process transforms stocks of highly concentrated and easily available resources [BASICS OF LIFE] (Faber and Manstetten 2010: chapter 8) into products and wastes which contain the same material in lower concentration. For instance, oil, which is found in the earth's crust in high concentration and in a state of low entropy, serves as fuel, while CO_2 is evenly distributed throughout the atmosphere in a state of high entropy. G-R stresses that these economic processes are irreversible in time: The stocks of resources (like oil, coal and ores) are permanently reduced by economic actions. At the same time the stock of wastes from the economic process is permanently increased.

The observation that energy and matter are transformed in economic processes from a state of easy availability (highly dispersed waste) led G-R to the assertion that the economic process is subject to the Second Law of Thermodynamics: 'The economic process is entropic, it neither creates nor consumes matter or energy, but only transforms low into high entropy' (G-R 1971: 281). G-R criticises that Mainstream Economists have not yet taken the Entropy Law seriously. Since it deals with the available (useful) energy, it is, in G-R's words, the 'most economical of all physical laws' (G-R 1971: 280). 'Low entropy is a necessary condition for usefulness' (G-R 1979: 1042), thus the Entropy Law is essential for understanding economic value or scarcity" (Baumgärtner et al. 1995: 12).

3.3 Thermodynamics as an essential element of Ecological Economics

The application of thermodynamics is presently widely recognised as an essential element in much current ecological-economic thought since it gives rich insights into the nature of economy-environment interactions. The laws of thermodynamics lead us to recognise that the human economy is an open subsystem embedded in the larger, but finite, system of the natural environment (Boulding 1966, Georgescu-Roegen 1971, Daly 1977, Ayres 1978, Faber et al. 1995 [1983], Baumgärtner et.al. 2006 and many more).

"The usefulness of thermodynamics derives from its applicability to all real production processes, which are the basis of economic activity. Thus, thermodynamics relates ecological economics to the natural sciences, such as chemistry, biology and ecology, which also facilitates interdisciplinary research. The strength of the concept of joint production is that it allows us to incorporate this insight about economy-environment interactions into Ecological Economics. This can be seen in the following argument.

From a thermodynamic point of view, energy and matter are the fundamental factors of production. Every process of production is, at root, a transformation of these factors.

Hence, in this view production processes are subject to the laws of thermodynamics" (Baumgärtner et al. 1995: 3-4).

3.4 Joint production as an easy-to-use and easy-to-understand concept – capturing essential thermodynamic constraints

We have mentioned several times above how difficult the notion of entropy is to understand and apply correctly. For over two decades, we have endeavoured to facilitate this understanding. In the phenomenon of joint production [JOINT PRODUCTION], we found a connection between thermodynamics and economic activity.

"The notion of joint production is a fundamental concept of Ecological Economics. It relates the repercussion of economic activity to the environment. It describes the phenomenon that several outputs *necessarily* emerge from economic activity. These joint outputs may all be desired and/or undesired. The occurrence of joint production is well known since the beginnings of agricultural activity. An example is sheep farming: A sheep yields not only milk, it also yields wool and ultimately meat. All sectors of modern economies are characterised by joint production. This is particularly true in the chemical industry where the joint products are often useful. But in the meantime, everyone knows that the fact of joint production often yields unwanted goods, so called bads, which are unwanted because they damage the environment, such as dust, waste water, slug, CO_2.

A close relationship exists between joint production and thermodynamics, for it can be derived from the first two Laws of Thermodynamics that unwanted joint products are unavoidable in industrial production (Faber et al. 1998; Baumgärtner et al. 2006: 50-53).

One can describe the process of production as a transformation of a certain number of inputs into a certain number of outputs, each of which is characterised by its mass and entropy. From the Laws of Thermodynamics, it then follows that every process of production is joint production; that is, it results necessarily in more than one output (Faber et al. 1998; Baumgärtner 2000: chapter 4). In particular, industrial production processes which create low entropy (i.e. highly ordered) goods *necessarily and unavoidably* jointly produce high entropy (i.e. lowly ordered) by-products. For example, in the production of iron, one starts from iron ore. In order to produce the desired product iron, which has lower specific entropy than iron ore, one has to reduce the raw material's entropy. This is achieved by employing the low-entropy fuel, for example coke, which provides the energy necessary for this process. From a thermodynamic point of view, one may therefore consider production as a shifting of high entropy from the raw material to the waste product.

In that sense, the concept of joint production can capture the essential thermodynamic constraints on production processes as expressed by the First and Second Laws, through an easy-to-use and easy-to-understand economic concept" (Baumgärtner et al. 1995: 4-

5). An extensive description of joint production with an empirical illustration is given in the concept JOINT PRODUCTION.

While thermodynamic considerations belong to the conceptual foundations of Ecological Economics, this is not the case in Mainstream Economics.

4. Literature

The content of MINE originates from scientific work published in books and peer-reviewed journals. Quotes are indicated by a special typographic style.

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Faber, M, Niemes, H., G. Stephan (1995/1983) Entropy, Environment and Resources: An Essay in Physico Economics. Springer Verlag, Heidelberg. Reprinted with permission from Springer Nature Customer Centre GmbH (**Licence Number: 4474120026267**).

4.1 Recommended literature

Key literature

Baumgärtner, S., M. Faber and J. L.R. Proops (1995) "Entropy: a unifying concept for Ecological Economics", Discussion Paper No. 226, Department of Economics University of Heidelberg.

Faber, M., R. Manstetten and. L.R. Proops (2002) Ecological Economics. Concepts and Methods, Edward Elgar, Cheltenham, U., Northampton, Ma, USA. [Chapters 6 and 7 of this book deal extensively with thermodynamics].

Faber, M., H. Niemes and G. Stephan (1995/1983), Entropy, Environment and Resources: An Essay in Physico-Economics, 2nd ed. 1995, Berlin, Heidelberg and New York: Springer. English translation by Ingo Pellengahr from: Entropie, Umweltschutz und Rohstoffverbrauch: Eine naturwissenschaftlich ökonomische Untersuchung, Berlin, Heidelberg and New York: Springer, Translated into Chinese in 1990. [One of the first books introducing analytically thermodynamics into Ecological Economics. Chapters 3 and 4 provide an extensive introduction of the notion of entropy for non-physicists].

Georgescu-Roegen, N. (1971) The Entropy Law and the Economic Process. Harvard University Press, Cambridge/Mass. [The classic and unsurpassed monograph on the foundations of Ecological Economics].

Recommendations for further reading

Arrow, K. J. and G. Debreu (1954) “Existence of an equilibrium for a competitive economy”, Econometrica, 22: 265-290.

4.2 References

Thermodynamics

Balian, R. (1991) From Microphysics to Macrophysics I. Springer-Verlag, Berlin Heidelberg, New York. [An excellent overview of the historical development of thermodynamics.]

Boltzmann, L. (1877) Wiener Berichte 76: 373 ff.

Boulding, K.E., (1966) “The Economics of the coming Spaceship Earth”, in H. Jarrett (ed.), Environmental Quality in a Growing Economy, Baltimore and London, John Hopkins University Press: 3-14

Carnot, S. (1824) Réflexion sur la puissance motrice de feu et sur les machines propres à cette puissance. Bachelier, Paris.

Clausius, R. (1854) Fortschritte der Physik 10.[Classical Paper]

Clausius, R. (1865) Annalen der Physik, 125: 353ff. [Classical papers]

Iha, A. (2013) “What is the second law of thermodynamics?”, Guardian, 2013, December 1st https://www.theguardian.com/science/2013/dec/01/what-is-the-second-law-of-thermodynamics. [Good and very short introduction to thermodynamics.]

Kelvin, Lord William Thompson (1852) “On the universal tendency in nature to the dissipation of mechanical energy” Philosophical Magazine 4: 304ff. [A classical paper]

Stumpf, H. and A. Rieckers (1976) Thermodynamik (Thermodynamics), Vols. 1 and 2, Vieweg, Braunschweig.

Ecological Economics

Ayres, R. U., (1978) Resources, Environment, and Economics. Application of Materials/Energy Balance Principle, New York, Wiley.

Baumgärtner, S. (2000): “Thermodynamic of waste generation”. In K. Bisson and J. Proops (editors), Waste in Ecological Economics, Edward Elgar, Cheltenham, UK., and Northampton, MA, USA.

Baumgärtner, S. (2005) “Thermodynamic Models”, in J. Proops and P. Safonov (editors), Modelling in Ecological Economics, Edward Elgar, Cheltenham, UK, Northampton, USA: 102-129.

Baumgärtner, S., M. Faber and J. L.R. Proops (1995) “Entropy: a unifying concept for Ecological Economics”, Discussion Paper No. 226, Department of Economics University of Heidelberg.

Baumgärtner, S., M. Faber and J. L.R. Proops (1995a) “The use of the entropy concept I ecological economics”, Discussion Paper No. 227, Department of Economics University of Heidelberg.

Baumgärtner, S., Faber, M. and Schiller, J. (2006), Joint Production and Responsibility. On the Foundation of Environmental Policy, Edward Elgar, Cheltenham. [This book contains the research on joint production carried out in Heidelberg from 1990 to 2006. It is co-authored by ten researchers.]

Baumgärtner, S., Dyckhoff, H., Faber, M., Proops, J.L.R. and Schiller, J., (2001). The Concept of Joint Production and Ecological Economics. Ecological Economics, 36: 365-372. [The short paper is the conceptual basis for the concept Joint Production]

Boulding, K.E., (1966) “The Economics of the coming Spaceship Earth”, in H. Jarrett (ed.), Environmental Quality in a Growing Economy, Baltimore an London, John Hopkins University Press: 3-14. [A pioneering paper on Ecological Economics.]

Daly, H.E. (1977) Steady State Economics: the Economics of Biophysical Equilibrium and Moral Growth, San Francisco, Freeman. [A classic text on Ecological Economics].

Dyke, C. (1988) “Cities as Dissipative Structures”, in W.H. Weber, D.J. Depew and J. D. Smith (eds.).

Eddington, A.S. (1928) The Nature of the Physical World. Cambridge University Press, Cambridge.

Faber, M., F. Jöst, R. Manstetten and G. Müller-Fürstenberger (1996), ‘Kuppelproduktion und Umweltpolitik: Eine Fallstudie zur Chlorchemie und zur Schwefelsäureindustrie’, Journal für praktische Chemie (Chemikerzeitung), 338, 497–505.

Faber, M., R. Manstetten and. L.R. Proops (2002) Ecological Economics. Concepts and Methods, Edward Elgar, Cheltenham, U., Northhampton, Ma, USA. [Chapter 6 of this book deal extensively with thermodynamics].

Faber, M., H. Niemes and G. Stephan (1995/1983), Entropy, Environment and Resources: An Essay in Physico-Economics, 2nd ed. 1995, Berlin, Heidelberg and New York: Springer. English translation by Ingo Pellengahr from: Entropie, Umweltschutz und Rohstoffverbrauch: Eine naturwissenschaftlich ökonomische Untersuchung, Berlin, Heidelberg and New York: Springer, Translated into Chinese in 1990. [One of the first books introducing analytically thermodynamics into Ecological Economics. Chapters 3 and 4 provide an extensive introduction of the notion of entropy for non-physicists.]

Georgescu-Roegen, N. (1971) The Entropy Law and the Economic Process. Harvard University Press, Cambridge/Mass. [The classic and unsurpassed monograph on the foundations of Ecological Economics.]

Georgescu-Roegen, N. (1979) “Energy Analysis and Economic Valuation,” Southern Economic Journal 45: 1023-1058.

Koopmans, T. (1973) “Economics Among the Sciences”. American Economic Revue 69: 1-13.

Proops, J.L.R (1985) “Thermodynamics and economics: from analogy to physical functioning”, in W. van Gool and J.J.C. Bruggink (eds.), Energy and Time in the Economic and Physical Sciences. North-Holland, Amsterdam.

Information theory

Shannon, C.E (1948) “A mathematical theory of communication”, Bell System Technical Journal 27: 379-423, 623-656. (Reprinted in C.E. Shannon and Weaver, The Mathematical Theory of Communication, University of Illinois Press, Urbana ILL, 1949) [A classic paper on information theory.]

Shannon, C.E, and W. Weaver (1949) The Mathematical Theory of Communication, University of Illinois Press, Urbana ILL. [A standard work on information theory.]

Online-References

Goodreads-Website:

https://www.goodreads.com/quotes/947685-the-law-that-entropy-always-increases-holds-i-think-the (last access: 16.10.2018)

Wie-sagt-man-noch-Website:

http://www.wie-sagt-man-noch.de/zitat/18409/thermodynamik+ist+ein+komisches+fach.+das+erste+m.html (last access: 16.10.2018)