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Energy and entropy: a thermodynamic approach to sustainability

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Summary

Thermodynamics is a basic science that formulates the rules for the conversion of energy and matter from one form into another. It sets the physical limits for the evolution of and the developments in the world around us. In contradiction to the mechanical approach, thermodynamics indicates that economic growth leads to increasing disorder. More specifically, increasing the flows of energy and matter through society, as happens in the process of ongoing industrialization, leads to progressive depletion of available energy and matter or, otherwise stated, to increased entropy. Excessive entropy production is reflected in natural disorders such as the greenhouse effect, ozone holes, environmental pollution, etc. Sustainable development can only be approached by imposing a close to steady-state lifestyle on mankind.

Introduction

Since the appearance of the report by the Brundtland Commission in 1987 (Brundtland, 1987) the notion of sustainability or, preferably, sustainable development, has received much attention. It has become the environmental vogue word of the 1990s. In the Brundtland report the following definition has been given: 'Sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (Brundtland, 1987). Based on this definition, sustainable production involves obtaining a sufficient yield at a minimum cost of resources, i.e. of energy and raw materials. Because different communities of interests have different views on sustainable development, implementation is not unambiguous. However, in any approach, sustainable development requires a long-term strategy and outlining the strategy may be complicated because science and technology keep shifting the boundaries of human abilities to manipulate nature. However, nature itself does not shift its boundaries and, in view of this, sustainable development takes into account the constraints imposed by nature.

It is, pre-eminently, thermodynamics that indicates the boundaries within which processes in the world around us can take place. Thermodynamics deals with energy and matter and, in particular, with transitions of energy (and matter) from one form into another. The possibilities for such transitions are limited and the limitations are determined by the First and the Second Laws of Thermodynamics (Atkins, 1984).

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Thermodynamic background

The word 'energy' belongs to our daily vocabulary and usually refers to the ability to perform work. This is, as will be explained later, just one appearance of energy. It is not easy to give a precise definition of energy; it is a rather abstract notion. Each object ('system' in thermodynamic language) contains a certain amount of energy. Moreover, since Einstein's $E = mc^2$ it is recognized that matter and energy are equivalent. It is, however, impossible to determine the energy content of a given system and, therefore, ignorance remains about the energy of a system. This is not much of a problem; it is more important that changes in the energy content can be determined exactly. Such changes may result from two types of processes: (1) by performing work on the system or letting the system perform work and (2) by exchanging heat between the system and the environment (= rest of the universe).

The First Law of Thermodynamics deals with energy. This law is an empirical one. It states that energy cannot be created nor annihilated, i.e. the energy content of the universe is constant. This law, first formulated in the middle of the last century, was difficult to accept in the beginning. This is illustrated by the numerous, unsuccessful attempts do design a perpetuum mobile, a machine that performs work without input of energy. At first sight, this law of energy conservation seems to present good news: if the total amount of energy is constant, why should the human race be frugal in using it? The bad news is that interactions between a system and environment always go in a certain direction, a direction in which the energy that is available for performing work continuously decreases.

The Second Law of Thermodynamics is helpful in understanding the world and its environment. The law describes the direction in which nature unfolds. The Second Law of Thermodynamics indicates the difference between a dynamic (= mechanical) and a *thermo*dynamic world view. In a mechanical world, as described, for example, by Newtonian mechanics (Newton, 1687), events (= processes) are solely determined by forces. Such a description allows the process to occur in a reversed direction as well. For instance, according to Newton (1687), the planets could just as well orbit around the sun in the opposite direction. In the thermodynamic world, in addition to forces, entropy plays an important role, so that the course of events is in a direction that is experienced as progressing in time. An evident example is that heat flows from high towards low temperature and never in the opposite direction. Another example is that gas molecules in a container do not accumulate in a part of the available volume; on the contrary, they tend to distribute homogeneously. A similar phenomenon is observed after injecting a dye in water. Less visible, but just as real, are the distributions of, for example, exhaust gases and propellants in the atmosphere and of minerals from detergents and cattle feed (via the manure) in soil, surface waters and oceans. A third example showing the direction of processes is the impossibility of allowing a system perform work by extracting heat from an environment that has the same temperature as the system. If this were possible, a ball lying on the ground could lift itself, rivers could flow uphill and a ship could cross the ocean without wind or using fuel and all this could occur because heat is taken from the environment. In common experience it is just the opposite: the directed, coherent motion of the molecules of a falling ball is, upon hitting the ground, transformed into heat, i.e. a undirectional, incoherent movement of molecules. The same applies for the friction between the directionally moving river and ship and their respective environments. These examples are different manifestations of one principle: the natural tendency of things (in our examples heat, matter and coherence) to spread. This is related to the tendency of storing a constant amount of energy in the universe in as many ways as possible. This is the quintessence of the Second Law of Thermodynamics.

Entropy is the central notion in the Second Law of Thermodynamics. Although less familiar than energy, the word 'entropy' is slowly reaching the public. It is usually associated with randomness and chaos. This is in most cases more or less correct, but, more exactly, the entropy of a system is a measure for the number of ways the energy can be stored in that system. Thus, the direction in which events proceed goes along with an increase of entropy. The entropy variation of a system is defined as the heat flow into/from the system divided by the temperature (in kelvin) at which the heat transfer occurs. For a natural process, as heat flowing from a warm to a cold object, the entropy effect is indeed positive, because the entropy gain on the cold side (low temperature) is larger than the entropy loss on the warm side (high temperature). Based on the definition of entropy, it can be proven that any other natural process is accompanied by an entropy gain.

As explained above, heat cannot be fully converted into work, but, fortunately, heat can be partially used to perform work. This is illustrated in Fig. 1(a). Here, heat is drawn from a warm system so that the entropy of this system decreases. If all the heat arrives in the cold environment it would lead to an entropy gain there which overcompensates the loss in the warm system. Even if only a fraction of the heat taken from the warm system arrives in the cold environment the overall entropy effect would be positive, so that the remainder of the heat would be available to perform work. Steam engines operate according to this principle.

In the world around us numerous processes occur that, at first sight, seem to lead to an entropy reduction. The refrigerator, the operating mechanism of which is shown in Fig. 1(b), may serve as an example. The low temperature in the refrigerator is maintained by transporting heat into the warmer environment. This would result in a net entropy decrease and is therefore not in accordance with the Second Law of Thermodynamics. The heat flow from the cold refrigerator into the warmer kitchen is possible only if extra heat is added to the flow that arrives in the warmer environment. This is realized

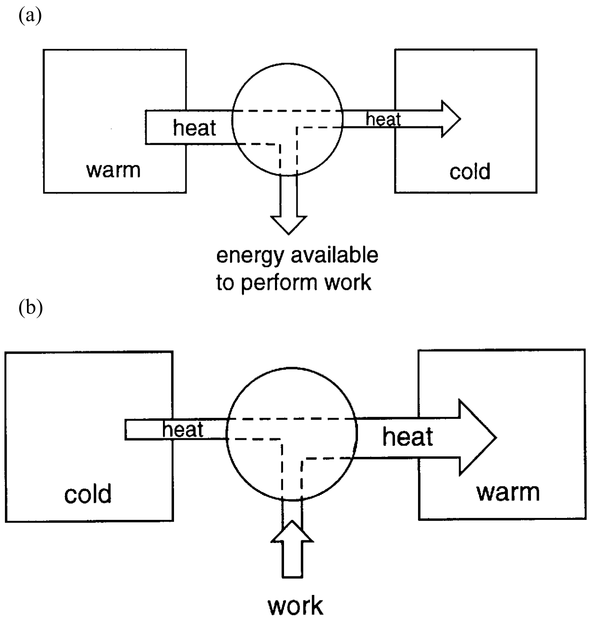

Fig. 1. (a) In a steam engine heat flows from a hot reservoir to a cold reservoir. Part of the heat flow is transformed into energy available to perform work. (b) In a refrigerator cold air is separated from warm air. Maintaining such order is only possible if heat is added to the flow arriving in the warm environment. For further explanation refer to the text.

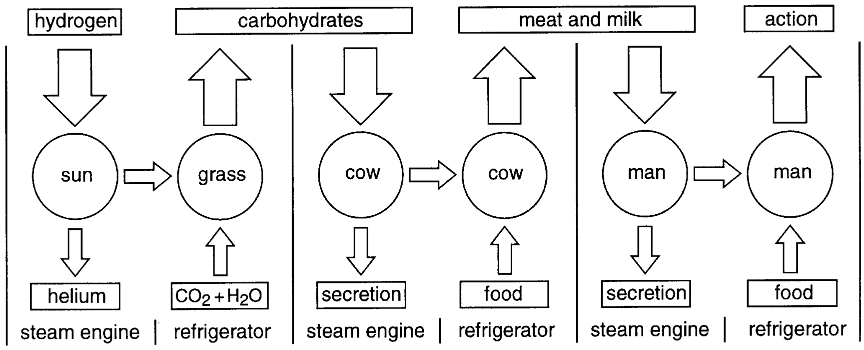

Fig. 2. Processes on the Earth use energy originating from the sun. These processes can be represented in a chain in which 'steam engine'–'refrigerator' couples are linked. Entropy is produced in the 'steam engine'.

by the electric motor of the refrigerator that converts electric energy into heat. In an electric power station entropy is produced, just as in a steam engine. Thus, a process like a refrigerator where cold is separated from warm and, hence, where order is maintained, can only take place if it is coupled to another process, like the one in a steam engine, where a heat flow is partly transformed in energy to perform work. The boundary condition is that the total entropy effect of these coupled processes is positive.

Observing the flows of energy and matter more closely, it appears that they are maintained by a sequence of 'steam engine'–'refrigerator' couples. In this analogy a 'refrigerator' is a system where the entropy is kept low by virtue of the input of available energy and in the 'steam engine' this energy is made available, accompanied by the production of entropy. Ordered low-entropy activity, as happens in the development and maintenance of, for example, biological organisms and edifices as well as in the manufacturing of products from raw materials, is coupled with the combustion of food in the organism and of fuel in the machinery. An example of such a 'steam engine' – 'refrigerator' sequence is shown in Fig. 2. Because the total amount of energy in the universe is constant, it is evident that as a result of the sequential entropy productions the energy available to perform work continuously decreases along the chain. The principle applies for other flows of energy and matter as well, for instance in the sequence grass–grasshopper–frog–fish–man or in raw material–transport–semi-manufactured article–transport–end product. As in each preceding link in the chain of events the entropy content is lower, it suggests that the origin of all processes in the universe represents a state of minimum entropy. This is in line with the idea that the development of the universe has started from a singularity of densely concentrated matter and energy. All events that have occurred thereafter and are still to occur are mutually interrelated in a complex way. Although low-entropic structures develop locally, the total amount of entropy in the universe continuously increases.

Sustainability in a historical and cultural perspective

The age of the planet Earth is estimated to be approximately 4-5 billion years and 'modern' man (*Homo sapiens*) appeared on the earthly stage just approximately 300 000 years ago. At first, man lived as a hunter–collector from natural products and when local resources became depleted he left his settlement to find a new place. For far the largest part of its existence mankind lived this way. Approximately 10 000 to 5000 years BC, at different locations on Earth, man started to domesticate crops and animals, which led to agriculture and animal husbandry. Such rural communities have been self-supporting for many centuries. There was no export nor import of products. Just like the hunter–collector the first farmer lived in direct relation to and in direct dependence on nature.

In some communities the agricultural production gradually exceeded the needs. This resulted in export which, in turn, stimulated the development of urban districts where traders and craftsmen settled. In this way (Western) economies were, for a long time, based on agriculture and home industry using renewable energy sources such as wood and other plants. This situation changed dramatically when, in the last half of the nineteenth century, the exploitation of fossil fuels started, first with coal and later mineral oil and natural gas. This, together with the appearance of the steam engine, made industrial production possible (and also in agriculture) and the process of industrialization is still going on. On the one hand, this led to an enormous economic growth in the industrial countries, but, on the other hand, it caused severe pollution in the world (soil, water and air).

As technology advanced, mankind felt independent and behaved more and more independently of nature. In particular, the discovery of huge stocks of fossil fuel has added to that attitude of independence. Now, as the finiteness of these stocks comes into sight and decline of ecosystems is experienced, it is realized that technology cannot 'liberate' man from nature. The advancement of technology is only possible within the boundaries set by nature.

Society and its technologies determine, to a large part, man's world view. In addition, other aspects, in particular religion and science, play important roles. Most Eastern religions consider history and the future to pass in cycles. For instance, an 'equal partnership' between man and nature and 'cosmic unification' are central ideas in Buddhism. This implies a frugal lifestyle and a sparing use of energy and other resources. According to the Judaic–Christian consent the world develops linearly with a well-defined beginning and end. The biblical text (Genesis 1, 26–34) where God ordered man to fill the Earth, to subdue it and to have dominion over every living thing that moves upon Earth, has too often been used to justify the exploitation of nature by man.

In the industrial countries the mechanical world view, i.e. the world as a machine, is still the most popular one. It is rooted in the seventeenth century when scientists not only asked the question about the 'why' of things (which they tried to answer by philosophic reasoning), but also investigated the 'how' of events. This required experimentation. In their attempt to obtain objective knowledge the scientists tried to detach from the world around them. This led to a mathematical description of the world: everything in nature is interrelated in an orderly manner, which, in principle, can be caught in mathematic equations. By presenting mathematical equations describing matter in motion, Newton (1687) proved the rightness of this mathematical view. The success of the scientific development had its impact on social-economic ideas. Society is now regarded as ruled by a 'natural order': The 'natural' effort of the individual to possess more property leads to a better society. Public authorities should not interfere. Supported by this idea man behaves expansively. He tries to conquer nature to extract more from it. A piece of land that is not exploited should be regarded as 'lost' land; nature only has a value if it is productive. In such a mechanical world view, progression is associated with increasing order. This progression is thus brought about by man who has placed himself above nature from where he improves the world machine.

Although particularly amongst economists the mechanical world view is still popular, it wavers here and there to become replaced by a thermodynamic world view. If this development continues, the mechanical world view will have ruled for approximately 300 years, a rather short time period compared to the foregoing paradigms.

Sustainability in a thermodynamic world view

The whole physical world around us is energy: both dead objects (buildings, cars, etc.) as well as living organisms represent matter (= energy) plus work added to produce these things and to maintain them. When a building collapses, a car rusts away or an organism dies, the energy has not disappeared but has been transferred to somewhere else. Thus, as the final result of all events, energy and matter dissipate. Products have only a temporary value.

In the past, mankind has changed energy source various times. Such a change is usually ushered in by the scarcity and inaccessibility of the foregoing source. For instance, the hunter–collector became a farmer because of the scantiness of plants and animals in his environment. Switching from wood to coal was partially a result of excessive deforestation. As the existing energy source runs empty, more work has to be performed to extract useful energy (= energy available to perform work) from it. At a certain moment a break-even point is reached implying that, *per saldo*, the energy taken from the source is dissipated as entropy. When such a watershed is reached other energy sources should be sought.

Technology is nothing more than the transforming and transferring of energy and matter. Therefore, switching from one energy source to another requires adaptation of technology and this, in turn, may have large socioeconomic consequences. The exploitation of each next source in the sequence wood–coal–mineral oil implies more labour: cutting and chopping–mining–oil drilling and refining. In this development, machines have taken over from muscular work but a larger part of the energy dissipates as entropy. Furthermore, the transfer from renewable sources (solar, wind and water power) to non-renewable fossil fuels has strongly intensified the flow of energy and matter through society.

The industrial age is ruled by the growth-paradigm. Productivity is measured as a production rate. This approach has caused an increasing energy flow-through and further specialization so that in the course of the production process a large amount of energy is added to the product. For instance, the daily energy consumption in western societies amounts to approximately 600 000 kJ per person, whereas food supplies amount to only approximately 10 000 kJ. The difference is used for manufacturing food stuffs and other consumer goods, fuel for transportation and for the heating and cooling of buildings, etc. As an example, before a loaf of bread is sold in the supermarket the corn is transported from the farm via the corn chandler to the flour mill, where it is ground and processed further. From there it is taken to the bakery where various components are added and where the bread is baked and wrapped (in plastic!). Next, the bread is transported to the various stores from where it is taken by the consumer to bring it to their home. All this processing and manipulations require an amount of energy that exceeds the energy to grow the corn by an order of magnitude. This example, as well as many others that could be given, illustrates that in an industrial society man uses much more energy than in the preceding ages. In addition, since the beginning of the industrial revolution (the end of the nineteenth century) the world's population has increased dramatically: in the last 0.006% in the history of mankind the global population has grown by a factor of five

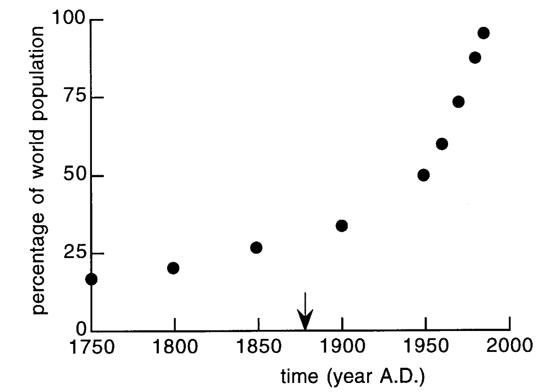

Fig. 3. World population since 1750. The arrow marks the beginning of the industrial revolution.

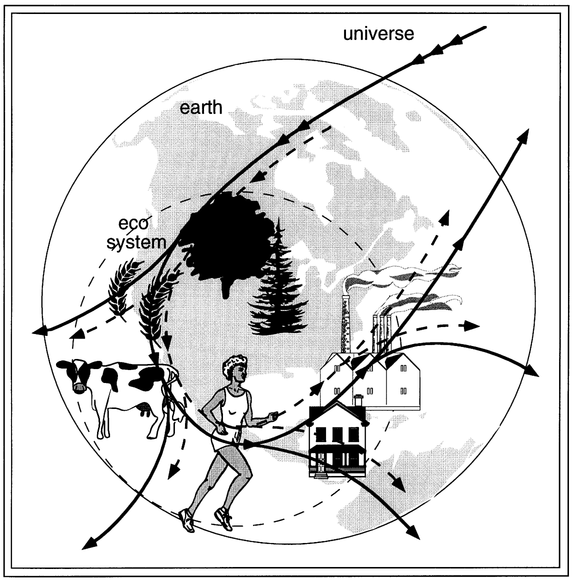

Fig. 4. Schematic representation of flows of energy (——) and matter (- - -) in the world. The Earth absorbs energy from sunlight and radiates heat into the universe. Matter dwells over the Earth but is not able to depart from it.

(Fig. 3).

The industrial revolution, based on the use of fossil fuels, not only resulted in factories, machines, cars and many other consumer goods, but also in the existence of an ‘extra’ 3–4 billion people. This enormous growth can be regarded as highly irresponsible when it is realized that in the course of a few hundred years man has used up most of the fossil fuels which the Earth needed some several billion years to accumulate. The mechanical conception, that increasing production and specialization leads to further structuring and order in the world, opposes the thermodynamic view. For increasing flows of energy and matter are accompanied by increasing dissipation and, therefore, by a larger entropy. This implies increasing disorder, which manifests itself in the pollution of the soil, water and air.

To preserve life on earth for as long as possible, i.e. for a real sustainable development, the loss of energy to perform work should be minimal. In other words, entropy production should be kept as low as possible. The physical boundary conditions for attaining such a sustainable development are explained below. The interactions between the universe, the Earth and its ecosystems (including living organisms and products of human activity) are depicted schematically in Fig. 4. By definition, the universe has no environment. There is no input or output of energy and matter. However, energy constantly flows through the universe, for instance from the Sun via the Earth back into space. Hence, the Earth is not an isolated system. It is practically a closed system, i.e. apart from some rare meteorites and a few space shuttles, the Earth does not exchange matter with its environment. By contrast, most ecosystems are open systems; they exchange both energy and matter with their environments.

As flows of energy and matter are accompanied by an increasing entropy, will there ever come an end to the entropy production? This would imply that all energy is dissipated as entropy so that no energy is available for work any more. Everything would be in equilibrium, processes would have ceased to occur and life would have come to an end. Such a state is referred to as the ‘heat death’. Although this seems to be the final destiny of the universe, it should not be a worry because long before this occurs the Sun will extinguish making terrestrial life impossible. The question concerning the future of the Earth in the shorter run is more relevant.

It can be proven that the production of entropy is at a minimum if a process occurs under steady-state conditions (Prigogine, 1961). In a steady state the inputs of matter and energy into a system equals the respective outputs. (Note that this is not an equilibrium state, because processes are still occurring.) However, living systems cannot reach a steady state, because part of the energy input is not carried off but is used to keep up the structure of the organism. During the eras of the hunter–collector and the pre-industrial farmer, ecosystems approximated to a steady state very closely, so entropy production was about the lowest necessary to sustain the systems. This has been changed drastically with the emergence of industrialization. Three different scenarios could, in principle, restore the close to steady-state situation. In the first two, the large energy flow-through could be maintained, whereas the third one implies a strong decrease of this flow. These scenarios are as follows.

(1) Nuclear fusion may be regarded as a promising future source of concentrated energy. However, there are quite a number of technical problems that seem unsolvable. Furthermore, the terrestrial supply of lithium (that serves as a substrate for one of the nuclei to fuse) is rather limited.

(2) Some people believe that by applying

molecular-biological techniques, such as genetic engineering, conversion of energy can be made much more efficient and even new forms of renewable energy sources can be created. Such a biotechnological era seems, for the time being, science fiction.

(3) In this scenario, economic activities are adjusted to the renewable energy sources of the Sun, wind and water. It implies low-scale energy consumption and the technological infrastructure has to be adapted accordingly.

At first sight, the first two scenarios may seem most desirable. However, their successes are highly questionable, because maintaining a high flow-through of energy includes a further problem. In each process, the conversion of energy is linked to the conversion of matter and an intensive flow of energy therefore implies an intensive flow of matter. Matter cannot leave the closed system of Earth and, because of the action of the Second Law of Thermodynamics, matter will dissipate over the planet and not be available any more. This increase of matter entropy is larger the stronger matter flows through society.

If, in a closed system, the amount of available matter decreases, why would it not be possible to replenish it by producing matter from energy on the basis of Einstein's $E = mc^2$? The answer is that matter can never be produced from energy alone. To produce a certain component other components are required. The reversed process does take place: in natural nuclear reactions matter is transformed into energy.

Is it not possible to collect scattered matter according to the refrigerator principle? Yes, that is very well possible for waste, i.e. matter that is useless but that is still available, such as broken bottles, old newspapers, used tyres and so on. However, the recycling process itself (transport, processing, etc.) contributes to the entropy production as well. Hence, recycling is never 100% effective. As far as they are not incorporated in bio(geo)chemical pathways, really dissipated matter, such as gases emitted into the atmosphere and components that are dissolved in groundwater, surfacewater and seawater, cannot be recollected. This matter is irrevocably lost for reuse; thàt is the message of the Second Law of Thermodynamics.

The dissipation of matter will be reduced if bounds are set to the flow-through of matter and, because of the indissoluble connection, to the flow-through of energy. Hence, to postpone the scarcity of matter on the planet as long as possible, the third scenario is the only option. According to that scenario the industrialized world has to give up a large part of its materialistic prosperity and it should return to an equal partnership with, instead of conquering and manipulating, nature.

The crucial question is to what extent is the human race willing to adjust its lifestyle in favour of prolonging a liveable world? If it lacks such a willingness it will be faced with the consequences of excessive entropy production such as the greenhouse effect, ozone holes, acid rain, pollution of soil and water, etc. The era of industrial progress may then turn out in the end to be the era of ecological destruction.

Conclusion

The Second Law of Thermodynamics guides the human race and its future. It helps humankind to understand how the world and life therein could have evolved and, at the same time, it points to the finiteness of the evolution. It must be accepted that this is a law of nature. The choice of route is in the hands of the human race.

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