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On exergy and sustainable development—Part 1: Conditions and concepts

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Abstract—The future of life on our planet is a matter of great concern. This paper is based on a vision of sustainable development. It is divided into two parts. The first part introduces conditions and concepts that are of importance for sustainable development. Environmental conditions in terms of causes and effects of emissions, the concept of exergy as a physical measure of difference or contrast and a number of different exergy forms common in nature are presented. Emissions and pollutants are differences in the environment, thus effecting the environment. Exergy is a suitable measure of these differences. The concept of sustainability is examined with relation to exergy flows on the earth. Part 2 of this paper introduces methods based on presented concepts and applies these to real systems. Exergy is applied to emissions to the environment by case studies in order to describe and evaluate its values and limitations as an ecological indicator. Exergy is considered as a useful ecological indicator by reference to the literature in the field. © 2001 Éditions scientifiques et médicales Elsevier SAS

Nomenclature

c	speed of light in vacuum $= 3.00 \times 10^8$ m·s^{-1}	
c	concentration	
c_i	concentration of substance i	
c_{i0}	concentration of substance i in the environment	
C	heat capacity	J·K^{-1}
e	exergy per unit area	J·m^{-2}
E	exergy	J
E^{tot}	total exergy	J
E_{in}	exergy input	J
E_{out}	exergy output	J
E_{st}	structural exergy	J
H	enthalpy	J
I	information	bit
i	unit $= 1, 2, \ldots$	
j	unit $= 1, 2, \ldots$	
k	Boltzmann constant $= 1.38054 \times 10^{-23}$ J·molecule^{-1}·K^{-1}	
m	mass	kg
n_i	number of moles of substance i	mol
N	Avogadro's number $= 6.022 \times 10^{23}$ molecule·mol^{-1}	
P	pressure	Pa
P_0	pressure of the environment	Pa
P_i	partial pressures of gas i	Pa
P_{i0}	partial pressures of gas i in the environment	Pa
P	probability	
P_j	probability of state j	
P^0	probability at equilibrium	
P_j^0	probability of state j at equilibrium	
Q	heat	J
R	gas constant $= 8.314$ J·mol^{-1}·K^{-1}	
S	entropy	J·K^{-1}
$S_{\mathrm{eq}}^{\mathrm{tot}}$	entropy of the total system, i.e., the system and the environment	J·K^{-1}
T	temperature	K
T_0	temperature of the environment	K
u	(internal) energy per unit area	J·m^{-2}
U	(internal) energy	J
V	volume	m^3
W	work	J
ΔQ	heat added to a system	J
ΔU	change of the internal energy of a system	J
ΔW	work extracted from a system	J

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μ	chemical potential	$\mathrm{J{\cdot}mol^{-1}}$
$\tilde{\mu}_i$	generalized chemical potential of substance i	$\mathrm{J{\cdot}mol^{-1}}$
$\tilde{\mu}_{i0}$	generalized chemical potential of substance i in its environmental state	$\mathrm{J{\cdot}mol^{-1}}$
μ_i^0	chemical potential for substance i in relation to its standard state	$\mathrm{J{\cdot}mol^{-1}}$
μ_{i0}^0	chemical potential for substance i in the environment in relation to its standard state	$\mathrm{J{\cdot}mol^{-1}}$
σ	Stefan–Boltzmann constant $\approx 5.67 \times 10^8\ \mathrm{W{\cdot}K^{-4}{\cdot}m^{-2}}$	
Ω	number of possibilities	

1. INTRODUCTION

The future of life on our planet is a matter of increasing concern, as we are being confronted with several warnings about the growing fragility of the earth's life support system. A vision of sustainable development is carried by a number of international declarations as 'Agenda 21' of the Earth Summit held in Rio de Janeiro in 1992 and by the ongoing work of the Encyclopedia of Life Support Systems (EOLSS, see http://www.eolss.com). The EOLSS will, via the Internet, offer a living source of essential knowledge of the earth's life support systems for humanity to live and thrive in symbiosis with nature. It is this vision of sustainable development that has inspired us in the writing of this paper as well as in most of our work.

In 1977, Wall [1] outlined the basic ideas required to incorporate the concept of exergy into the accounting of natural resources. In this work the use of energy and material resources in human society were treated in terms of exergy, and exergy analysis was proposed as a method for calculating the total exergy use of a product or a service. The necessity to distinguish between resources originating from deposits, funds and natural flows was also pointed out, as well as the need for an increasing concern for environment issues. In 1978, Szargut [2, 3] suggested that 'the index of cumulative consumption', i.e., the loss of exergy of deposit resources, can be redefined as an index of ecological costs. Wall in 1993 proposed the use of exergy of emissions as an indicator of environmental effects and, independently of each other, Wall in 1993 [4] and Hirs in 1994 [5] have proposed an exergy tax. Wall bases this tax on the exergy of used deposits and exergy of emissions to the environment, whereas, Hirs bases it on the exergy losses. Ayres and Martinàs [6] stated that in the case of a waste residual, exergy could be regarded as the potential for doing harm to the environment by driving undesirable and uncontrollable reactions with components of the environment. Finnveden and Östlund [7] have successfully introduced exergies of natural resources into the methodology of environmental life cycle assessment. The authors have proposed the method called Life Cycle Exergy Analysis (LCEA) that incorporates both a distinction between renewable and non-renewable resources as well as the total in and out flows of exergy during a product life cycle [8]. Cornelissen [9] has proposed a similar method called Exergetic Life Cycle Analysis (ELCA), where the exergy destruction is used as a single criterion for the depletion of natural resources. Later a distinction between renewable and non-renewable resources was added [10]. A research project called 'Exergy as an Environmental Indicator' is currently underway at the University of California, Berkeley. This was partly initiated by a pioneering work of Connelly [11] in order to introduce exergy into the field of Industrial Ecology. Jørgensen and Nielsen [12] emphasize that exergy can be used as an ecological indicator, as it expresses energy with a built-in measure of quality. It measures the energy that can do work, e.g., the chemical energy in biomass. The Energy Logistic Modeling (ELM), developed by Blinge [13] may also include the exergy of inputs and outputs, e.g., emissions to the environment. An investigation of exergy as an ecological indicator was recently presented by Gong [14]. From this study it is obvious that exergy will be further applied as a useful concept in the environmental field. Rosen and Dincer [15] recently presented an application of exergy analysis to waste emissions. They concluded that exergy can make a substantial contribution to the evaluation of environmental problems. The concept of exergy successfully links the fields of energy, environment, and sustainable development. From these works it is obvious that exergy is gradually being adopted as a useful tool in the development and design of a sustainable society.

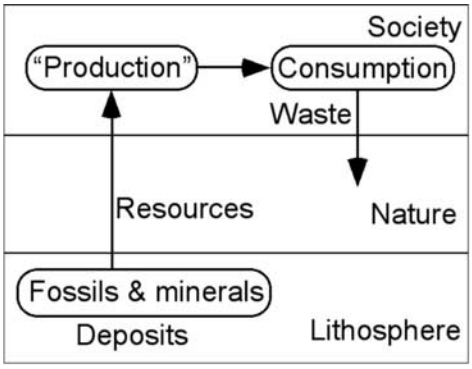

Figure 1. Resource use by the society.

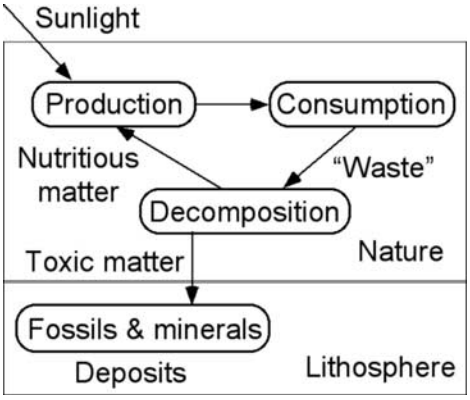

Figure 2. Resource use by nature.

Present industrial society is built on a non-sustainable resource use, see *figure 1*. Substances, such as fossil fuels and metals that originate from deposits of fossils and minerals in the lithosphere are unsealed and spread in the environment, which is the opposite of what is done by nature, see *figure 2*. In nature these substances are instead being accumulated and sealed as deposits.

Resource use by nature is characterized by the recycling of matter, which is forced by the inflow of sunlight. This will be further treated below. Natural processes, acting for billions of years, have built up the deposits in the lithosphere. By this, nature has also created conditions suitable for life on the earth, e.g., the availability of oxygen in the atmosphere and the removal of unwanted and toxic substances from the biosphere. Thus, when these substances are released as waste (see *figure 1*), the living conditions in the environment change. These environmental effects are often difficult to understand and impossible to predict. Some of the reasons for this are: (1) the diversity of nature, with an enormous amount of species in constant interaction with each other; (2) most of the interactions occur at a microscopic level, i.e., between microscopic organisms such as bacteria, viruses and fungi; (3) the environment, i.e., the ecological system with all its subsystems and parts has a very high level of complexity; (4) the environment is a living system, i.e., it lives by itself. Thus, it is in a state of constant and unpredictable change; (5) our ability to understand nature is limited, since human beings are just a part of nature. Nature is and will always be far more intelligent than human beings and man made systems; (6) evolution is an unpredictable characteristic of nature that humans will never be able to fully understand. Nature is so complex and innovative that science can continue to discover new patterns forever. However, science will never achieve a complete understanding of nature. Also, the present division of science into separate disciplines does not facilitate a general awareness of the behavior of nature. So-called primitive people, e.g., native or indigenous people of America, Africa and Australia, often exercise a more wise and sustainable behavior, probably based on a better understanding of human beings as well as nature.

Thus the behavior and function of the environment, in principal, is impossible to fully understand and predict, even though, we are becoming increasingly obliged to pay more attention to the environment. This is becoming more and more important as modern industrial society imposes even more burdens on nature. A major thesis motivating our work is that engineering, as well as economics and other development policies should be reoriented to better respect the earth's carrying capacity and to guide human actions so as not to violate the conditions of sustainability of life on this planet. Thus, it is our hope that this paper will offer a tentative outline of fundamental conditions, concepts and methods to be further elaborated and developed in order to support our common efforts to gain further understanding on these topics and to achieve sustainable development. However, in addition to this we also are required to adopt a responsible attitude to the unknown. This is when concepts such as morals, wisdom and emotions may be of importance [16].

2. ENVIRONMENTAL CONDITIONS

The environment may be divided into five spheres:

(1) biosphere,
(2) lithosphere,
(3) atmosphere,
(4) hydrosphere, and
(5) sociosphere,

that are in constant interaction with each other. The biosphere has transformed nature into its present state, where evolution can be regarded as the driving force. One of the major impacts relates to photosynthesis, in which carbon dioxide is separated into carbon and oxygen. Some of this carbon is put away in the global store of fossil 'fuel' in the lithosphere, and oxygen is emitted to the atmosphere, which is composed of nitrogen (about 78%), oxygen (about 21%), argon (about 1%), carbon dioxide, water vapor, ozone and other gases. Water, mainly in the hydrosphere, appears simultaneously as ice, liquid water and water vapor. This makes the earth unique among the planets of our solar system. Furthermore, water is an enormous heat reservoir, thereby balancing temperature variations both in space and in time on the earth's surface. The lithosphere is the solid bedrock with all its minerals and salts, which by natural erosion are dissolved and become important nutrients in water. The biosphere consists of all living organisms on the earth with the exception of modern man, which belongs to the sociosphere, together with all the man-made systems. Plants and animals consequently belong to the biosphere, and buildings and machines belong to the sociosphere. Only so-called primitive people and their artifacts belong to the biosphere. The main difference between the sociosphere and the biosphere is depicted by *figures 1* and *2*, respectively. Sedimentation, ozone depletion, green house effect, DDT and PCB contamination in the biosphere are further examples of interactions between these spheres. Exergy is consumed in the constant flows of energy, matter and information that go on within and in-between these spheres. The driving force is exergy that mainly originates from the contrast between the sun and space. This will be further explained below.

It is important to make a clear distinction between cause and effect of environmental problems. The actual cause behind an observed effect is not always possible to derive in detail. Sometimes several causes act together or one cause may have a number of effects. Different causes may also generate the same effect. Causes and effects, generating new effects, and so on are linked in an almost endless process of change, often impossible to fully understand or predict. However, below is a tentative classification of some causes and effects. This also shows the complexity behind what we call environmental effects. The causes are named with relation to complexity, thus, physical causes come first.

(i) Physical changes and causes are often easy to measure, e.g., a change of temperature, pressure, humidity, physical shape, mechanical properties, color, composition and nuclear radiation. When dams are built, the landscape is physically changed; an artificial lake is created which has a strong effect on the local ecological system. When forests or agricultural land are made more productive by draining, the local ecological system is often completely ruined and water is lost from the ground. The clear-cutting of forests often leads to flood after heavy rain and this can remove the fertile soil and destroy the ecosystem. The cutting down of rain-forests usually results in removal of nutrients and some measure of desertification. The emission of green house-gases, e.g., CO_2 and CH_4, are also examples of the physical causes that affect the ambient temperature on the earth.

(ii) Chemical causes are more difficult to measure since they often involve several different chemical reactions that may be hard to describe in detail. An example of this is the depletion of the ozone layer in the atmosphere, which is caused by, e.g., the emission of CFCs and substances emitted by aircraft. The chemical composition of the environment is today heavily effected by emissions from human society. Modern farming uses artificial fertilizers and pesticides, and these produce complex and undesirable biological effects. The use of detergents in the household causes eutrophication in the local environment.

(iii) Biological causes can be new microorganisms, diseases, plants, and animals, and changes in their relative abundance. When plants and animals are introduced into an ecosystem, this may have tragic effects. Rats and feral cats have had devastating effects on the indigenous fauna of ocean islands. Sheep and goats in semi-arid parts of Africa may graze the ground so that savanna is replaced by desert. Careless treatment of human feces may also create new diseases. Rivers and lakes that are overloaded by human faces will reduce the oxygen content and new microorganisms and processes will appear. Their presence may be revealed by the offensive and toxic smell of hydrogen sulfide, which is apparent in many cities in the developing world today.

(iv) Ecological causes relate to effects by an ecosystem, i.e., the interaction between many species and not just individual species as above. Natural evolution, as described by Darwin, is an example of this. The evolution of life on the earth led to major changes in the physical and chemical composition of the global environment, e.g., the increased content of oxygen in the atmosphere and the removal of toxic substances from the biosphere.

(v) We may also find social causes behind environmental effects, e.g., when poverty and starvation bring people to destroy what is left of their local environment. War is a social activity of organized madness that creates horrible effects not only to the environment but also to people.

Effects are related to causes in different ways. Some effects are immediate and easy to relate to a cause; other effects take a very long time and may be very difficult to relate to a specific cause. Time is always part of the cause and effect relation. Effects are often also related to a number of causes, which sometimes also are acting together in a non-predictable way. We also have to consider the time-delay between the cause and the effect, i.e., short versus long term cause and effect relations. Substances that are biodegradable will have an immediate effect on the environment, which is often harmful, whereas non-degradable substances, e.g., glassware and china, may have a negligible effect. However, non-biodegradable, or only very slowly degradable, substances that also have a catalytic or toxic effect may be extremely harmful for the environment. Obvious examples are DDT, PAHs such

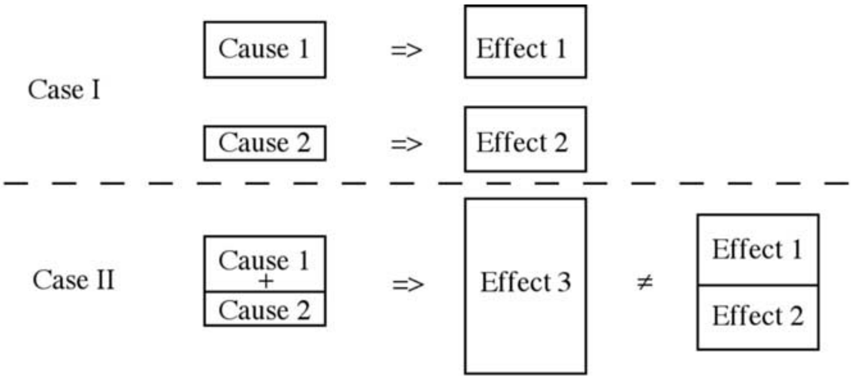

Figure 3. Case I: no synergetic effect; Case II: a synergetic effect.

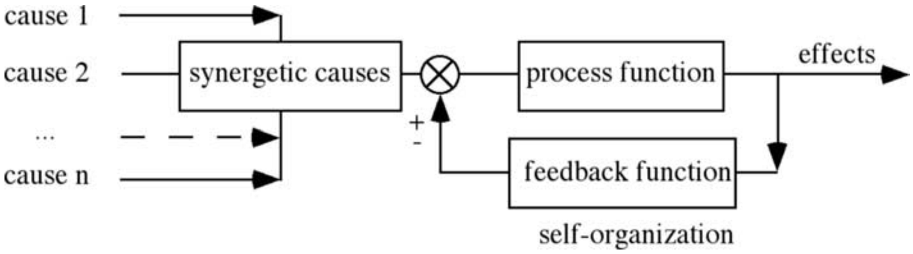

Figure 4. Synergetic and feedback effects acting together.

as benzo(a)pyrene and dioxins. Plastic bags floating in the sea will kill more turtles and drift-net will kill more sea lions and dolphins if they last longer by being non-biodegradable.

Causes sometimes act together so that the total effect becomes larger or smaller than for each cause acting by itself, see *figure 3*. This may be called a synergetic effect. Thus, causes that have a synergetic behavior must be related to other causes, e.g., catalytic relations. This makes it often impossible to predict the full consequences of an emission to the environment, since it must also be related to other emissions or substances that, by different causes, may appear in the environment.

There may also be feedback relations acting, see *figure 4*. This can be negative or positive, i.e., either leading to an acceleration or elimination of the effects. For instance, sulfur emission causes a positive feedback effect since it makes rain more acidic, thus increasing the erosion, which implies additional sulfur to emit from the lithosphere. Effects may also act as a cause to other effects thus creating a chain reaction, or a very complex pattern of linked causes and effects.

Environmental indicators can be linked to either causes or to effects. When measuring an emission this relates to a cause, and when measuring the number of animals facing range reduction or extinction this relates to an effect. A main problem with effects is inability of prediction. In many cases it is hard to predict the environmental effects. In some cases it is even impossible, i.e., when new diseases occur from the evolution of new microorganisms [16]. This will be further treated below, but we will first introduce the concept of exergy.

3. EXERGETICS

In 1824 Carnot [17] stated that the extractable work of a heat engine is proportional to the temperature difference, which later led to the definition of the second law of thermodynamics. Gibbs [18] introduced the notion of available work, including the diffusion term, in 1873.

Exergy is a thermodynamic potential; it is a general measure of work, ‘difference’ or contrast. It has been interpreted as ‘available’ energy by Keenan [19] and in 1953 the term exergy was suggested by Z. Rant to denote ‘technical working capacity’ [20]. In 1961 Tribus linked classical thermodynamics with information theory [21], through the entropy and the exergy concepts. In 1977

Wall offered a concise theory of exergy and introduced exergy as a useful concept not only in engineering but also for improving the resource use and reducing environmental destruction [1, 22]. At a conference in Rome in 1987, it was agreed among the participants to encourage strongly the use of exergy for the general concept of the potential to cause change, in lieu of terms such as availability, available energy, essergy, utilizable energy, work potential, available work, convertible energy, etc. 'The term exergy will be preferred for use in all future conferences, symposia, and workshops involving the participants' [23]. Recently, the concept of exergy has become widely accepted and used, and the International Journal of Exergy is a good example of this.

Thermodynamics provides the concepts of temperature T, pressure P, heat Q, work W, energy U, entropy S and four laws of thermodynamics:

0th law defines the concept of temperature.

1st law defines energy as a conserved quantity and work, as a product between an intensive and an extensive quantity, i.e., pressure and volume V, respectively:

$$\mathrm{d}Q = \mathrm{d}U + \mathrm{d}W \tag{5}$$

$$\mathrm{d}W = P\,\mathrm{d}V \tag{6}$$

2nd law defines the concept of entropy through heat:

$$\mathrm{d}S \geqslant 0, \qquad \mathrm{d}S_{\mathrm{reversible}} = 0 \tag{7}$$

$$\mathrm{d}Q = T\,\mathrm{d}S \tag{8}$$

and heat, as a product between an intensive and an extensive quantity, i.e., temperature and entropy, respectively, analogous to equation (6).

3rd law defines the zero level for entropy.

Thermodynamics only treats *reversible* processes, i.e., processes with no direction, for systems in *equilibrium* states. Thus, a more proper name is thermostatics [21]. Even though, thermodynamics is one of the most useful branches of physics in engineering, or as Einstein phrased it: 'This is the only general physical theory, I am sure of it, which in its basic conceptions will never be disproved'. The later established fundamental link to information theory by Tribus [21] is a good example of this.

The first law, i.e., energy conservation, generally fails to identify losses of work and potential improvements or the effective use of resources, e.g., in an adiabatic throttling process. The second law shows that, for some energy forms, only a part of the energy is convertible to work, i.e., the exergy. *Table I* summarizes the main differences between energy and exergy. Exergy will be further explained below.

Equation (2) is known as the Gouy–Stodola theorem [24, 25]. Gouy and Stodola discovered, indepen-

TABLE I
Energy versus exergy.

Energy	Exergy
The first law of thermodynamics	The second law of thermodynamics
'Nothing disappears'.	'Everything disperses'.
Energy is motion or ability to produce motion.	Exergy is work, i.e., ordered motion, or ability to produce work.
$\Delta Q = \Delta U + \Delta W$ (1)	$E = T_0 \Delta S^{\mathrm{tot}}$ (2)
where: ΔQ is added energy as heat to the system, ΔU is the change of the internal energy U of the system, ΔW is extracted energy as work from the system.	where: E is the exergy, T_0 is the temperature of the environment, ΔS^{tot} is the change of the entropy of the total system S^{tot}, i.e., the system and the environment.
$U = mc^2$ (3)	$E = k \ln 2 T_0 I$ (4)
Energy U and matter m is 'the same thing'. Everything is energy.	Exergy E and information I is 'the same thing'. Contrast is exergy.
Energy is always conserved, i.e., in balance; it can neither be produced nor consumed.	Exergy is always conserved in a reversible process, but reduced in an irreversible process, i.e., real processes. Thus, exergy is *never in balance* for real processes.
Energy is a measure of quantity.	Exergy is a measure of quantity and quality.

dently of each other, the law of the loss of maximum work. The work obtained is always smaller than the maximum work, because of the irreversibility. Equation (3) is the well-known formula, stated by Einstein, where U is energy, m is mass, c is the speed of light in vacuum, which is equal to about 3×10^8 m·s^{-1}. From equation (4) we see that, $k\ln 2T_0 \approx 2.9 \times 10^{-21}$ J is the amount of exergy of one bit of information at room temperature [1], where I is information, or information capacity (bit) and k is the Boltzmann constant, 1.38054×10^{-23} J·molecule^{-1}·K^{-1}. (The gas constant R, 8.314 J·mol^{-1}·K^{-1}, which appear in the ideal gas law, is simply Avogadros number, 6.022×10^{23}, i.e., the number of molecules in one mol, times k.) The concept of quality, which is used in *table I*, may be indicated by the concept of entropy S, however, as lack of quality, i.e., a measure of disorder. Thus, the concept of negentropy $-S$, which is a measure of quality or order, is sometimes used instead.

The exergy E of a system is expressed by:

$$E = U + P_0V - T_0S - \sum_i \tilde{\mu}_{i0}n_i \tag{9}$$

where U, V, S, and n_i denote extensive parameters of the system (internal energy, volume, entropy, and the number of moles of different chemical materials i) and P_0, T_0, and $\tilde{\mu}_{i0}$ are intensive parameters of the environment (pressure, temperature, and generalized chemical potential). These terms may be described accordingly: U is the energy carried within the system itself, part of this energy is useless as work, i.e., exergy. This part is defined by the last two terms. P_0V is the work captured as a volume V that occupies a space of the environment of pressure P_0. This is pure work. T_0S is the part of the energy U, which is useless due to lack of order $-S$, or heat at ambient temperature T_0. Similarly, the last term is another useless part of the energy U. In this case as substances at ambient states. The energy that is carried by substances can only be used 'down to' the level that is given by the environment. This is similar to the available potential energy of a waterfall or the carrying capacity of a ship, which is the total capacity minus the ballast.

From equation (9) we may also derive all other thermodynamic potentials, e.g., the Gibbs free energy, the Helmholz free energy, and the enthalpy, as special cases of exergy. Thus, exergy is the most general expression of thermodynamic potential, and an explicit derivation has been given by Wall [1], based on the works of Gibbs [18] and Evans [26].

Analogously, the exergy of a flow can be written as:

$$E = H - T_0S - \sum \tilde{\mu}_{i0}n_i \tag{10}$$

where H is the enthalpy, which captures the internal energy U and the external energy P_0V in a way that simplifies calculations.

Exergy is the maximum amount of work that can be extracted from a system. If exergy is defined as the maximum work potential of a material or of a form of energy in relation to its environment, then the environment must be specified, i.e., a reference environment. Usually average values of the earth are selected, i.e., reference temperature T_0 is 298.15 K and the reference pressure P_0 is 1 atm. However, the earth is not in equilibrium, actually it is far from equilibrium. The temperature varies from place to place. In some cases a local temperature should be used as reference temperature, e.g., when considering space heating or air-conditioning systems. The pressure and the chemical composition also vary around the globe. Thus, a local environment is sometimes also preferable [1]. The deposits of fossil fuels and the existence of oxygen in the atmosphere also build up a huge chemical potential.

The major conceptual issue is the choice of reference state to which the chemical reactant under consideration is to be compared. Usually the standard state of each element is defined as its pure elementary state, such as C for carbon, O_2 for oxygen, N_2 for nitrogen, and so on. The pure elements are normally assigned zero values of Gibbs free energy of formation. Szargut et al. [27] suggested that the standard chemical exergies are calculated on the assumption that the environment consists of a number of reference substances, one of each chemical element, with standard concentrations based on the average concentration in the natural environment. The reference substances selected fall into three groups, gaseous compounds of the atmosphere, solid substances from the lithosphere, and both ionic and nonionic substances from the oceans. It is claimed that the departure of the actual environment from the standard environment only occasionally introduces significant errors.

Exergy appears in many different forms of which work is the most basic form. Below we will use the symbol E to indicate the exergy of a change from a given reference state, at which $E = 0$.

$$W = E - T_0\Delta S^{\text{tot}} \tag{11}$$

From the second law we have that the total entropy change ΔS^{tot} is always positive for real processes. Only, for reversible process, i.e., when $\Delta S^{\text{tot}} = 0$, all exergy will transfer to work. Thus, exergy gives an upper limit to the work that is extractable from any process.

Exergy is work, which may be force times distance, or pressure times volume, PV, which was described above, see equation (9). Below, the exergy of a number of other differences will be expressed, e.g., latent and sensible heat, light, material substances and information. Exergy often appears as heat and cold, i.e., a temperature difference. Assume that heat Q is transferred between two reservoirs at temperatures T and T_0, then the exergy becomes:

$$E = T_0 \Delta S^{\mathrm{tot}} = T_0 \left| \frac{Q}{T_0} - \frac{Q}{T} \right| = Q \left| 1 - \frac{T_0}{T} \right| \tag{12}$$

which is a generalization of the Carnot relation. The ratio between the exergy E and the energy of the transferred heat Q is called the *exergy factor* E/Q, see *figure 5*. When $T < T_0$, there is a lack of energy in the system, i.e., coldness, which is sometimes expressed as negative energy. However, the exergy is still positive. By definition exergy can only be positive, because, there is no such thing as negative work. The exergy factor E/Q strongly increases for low temperatures. When T tends to absolute zero temperature, i.e., 0 K or $-273.15\,^{\circ}\mathrm{C}$, then E/Q approaches infinite. This explains the difficulty to reach absolute zero temperature. At high temperature E/Q becomes closer to 1 (the solid line), i.e., higher temperatures generate more work in a heat engine. This relation is valid for latent heat that describes the exergy need to maintain the temperature in hot spaces, e.g., furnaces, stoves, ovens, or houses, as well as in cold spaces, e.g., refrigerators and freezers, or to keep a pleasant indoor climate by air-condition in a hot summer day. Exergy reflects better than energy that heat or cold is more ‘expensive’ when we need it the most. Thus, it is easier to generate cold in winter and heat in summer. Exergy values depend on the ambient conditions, e.g., waste heat to the environment carries a higher exergy in winter than in summer. This is an example of something obvious, which is not explained by the energy concept, but is immediately explained by the exergy concept.

The exergy of sensible heat like a body or flow with temperature T is slightly more complicated to calculate since the temperature of the body as well as the amount of remaining heat decreases when heat is removed. If the heat capacity C is constant, the exergy becomes:

$$\begin{aligned} E &= C(T - T_0)\left(1 - \frac{T_0}{T - T_0} \ln \frac{T}{T_0}\right) \\ &= Q\left(1 - \frac{T_0}{T - T_0} \ln \frac{T}{T_0}\right) \end{aligned} \tag{13}$$

The dotted line in *figure 5* indicates the exergy of different systems, e.g., waste heat and melted steel. In many cases, as for melted steel, the total exergy of a system of different temperature is a combination of latent heat and sensible heat, i.e., equations (12) and (13), respectively.

Assume a power station producing 1000 MW of electricity and 2000 MW of waste heat as energy power at the temperature of 310 K from cooling water at a local ambient temperature T_0 of 300 K. From equation (13) the exergy of the slightly warmed water that is discharged into the environment becomes:

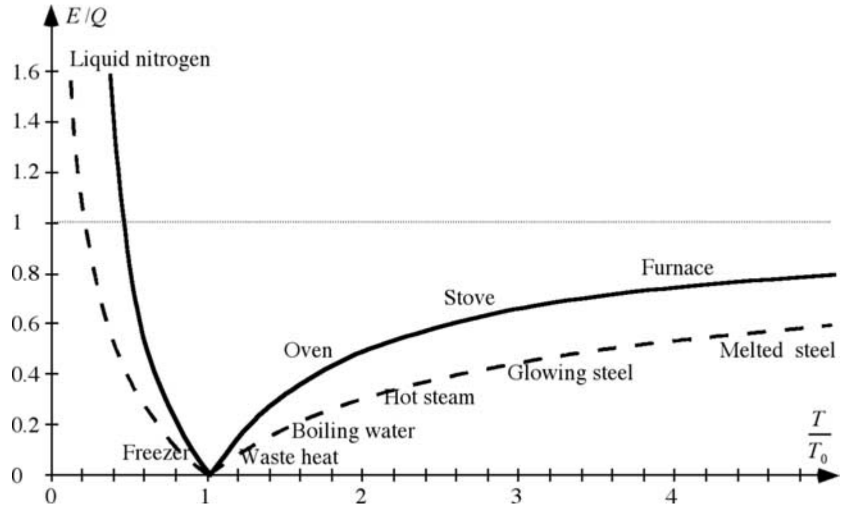

Figure 5. The exergy function of latent heat (solid line) and sensible heat (dotted line) as a function of its temperature.

$$\begin{aligned} E &= Q\left(1 - \frac{T_0}{T - T_0}\ln\frac{T}{T_0}\right) \\ &= 2000\left(1 - \frac{300}{310 - 300}\ln\frac{310}{300}\right) \\ &\approx 2000 \times 0.0163 \approx 33\ \text{MW} \end{aligned}$$

The discharge of 33 MW warmed water causes an increase of the local environmental temperature, which gradually changes the local ecosystem. The more exergy that is discharged into the environment, the more the damage will be to the local environment.

The exergy of light relates to the exergy power per unit area of black body radiation, which is

$$\dot{e} = \dot{u}\left[1 + \frac{1}{3}\left(\frac{T_0}{T}\right)^4 - \frac{4}{3}\frac{T_0}{T}\right] \tag{14}$$

where $\dot{u}$ is energy power emission per unit area, $\dot{u} = \sigma T^4$, and $\sigma \approx 5.67 \times 10^8$ W·K^{-4}·m^{-2} is the Stefan–Boltzmann constant.

The earth receives sunlight with $T_{\text{sun}} = 6000$ K and with $T_{\text{earth}} = T_0 = 300$ K, the ratio of the exergy flux to the total energy flux, i.e., the exergy factor becomes

$$\left(\frac{\dot{e}}{\dot{u}}\right)_{\text{sunlight}} = 1 + \frac{1}{3}\left(\frac{300}{6000}\right)^4 - \frac{4}{3} \times \frac{300}{6000} \approx 0.933$$

Transmission through the atmosphere changes the spectral distribution of solar radiation due to the selective absorption of radiation of the different gases that are present in the atmosphere, e.g., green house gases. It also varies with the composition of the atmosphere and the path length through the atmosphere determined by the position of the sun. The total solar energy power to the earth is about 1.7×10^{17} W, i.e., the solar energy power at right angles to the inflow is about 1367 W·m^{-2} before entering the atmosphere. The exergy is then about 1.6×10^{17} W and about 1275 W·m^{-2}, respectively.

The exergy of material substances can also be calculated. By assuming the pressure P and the temperature T to be constant, i.e., $P = P_0$ and $T = T_0$, the exergy becomes [1]

$$E = \sum_i n_i\left(\tilde{\mu}_i - \tilde{\mu}_{i0}\right) \tag{15}$$

where $\tilde{\mu}_i$ is the generalized chemical potential of substance i in its present state and $\tilde{\mu}_{i0}$ is the generalized chemical potential of substance i in its environmental state. Further, assume that the substance only depart from the environment in chemical potential μ and concentration c. Also, assume that the chemical potential may be written as

$$\mu_i = \mu_i^0 + RT_0 \ln c_i \tag{16}$$

where μ_i^0 is the chemical potential of substance i in relation to its standard state, which is given from chemical tables, usually the pure element. Then the exergy becomes

$$E = \sum n_i\left(\mu_i^0 - \mu_{i0}^0\right) + RT_0 \sum n_i \ln\frac{c_i}{c_{i0}} \tag{17}$$

where μ_{i0}^0 is the chemical potential for the substance in the environment in relation to its standard state. For only one substance the exergy becomes

$$E = n\left[\mu^0 - \mu_0^0 + RT_0 \ln\frac{c}{c_0}\right] \tag{18}$$

Chemical reactions occurring in combustion processes often result in extensive exergy destruction. Evidently no energy losses occur in the reaction. Only exergy calculations show that the production of entropy can cause tens of percents of potential work to be destroyed in the reaction. This approach shows that an electrochemical membrane reactor or a fuel cell could reduce exergy losses dramatically. For pure reference components, which also exist in the environment, the chemical exergy consist of the exergy that can be obtained by diffusing the components to their reference concentration c_{i0}. For gases and if the ideal gas law is employed, this can be written as

$$E = nRT_0 \ln\frac{P_i}{P_{i0}} \tag{19}$$

where P_i and P_{i0} refer to the partial pressures of the gas in the emission and in the environment, respectively. If the power plant above, that was assumed to produce 1000 MW of electricity, is fueled by coal, C, with the exergy content of 410 kJ·mol^{-1}, at complete combustion and no exergy losses, beside the cooling water, we get a production of about 7.3 kmol·s^{-1} of CO_2, or from equation (19):

$$\begin{aligned} E &= nRT_0 \ln\frac{P_i}{P_{i0}} \\ &\approx 7300 \times 8.31 \times 300 \times \ln\frac{1}{300 \times 10^{-6}} \approx 148\ \text{MW} \end{aligned}$$

where we assume 300 ppm of CO_2 in the atmosphere. As we see, this is also a considerable part of the exergy use, thus reducing the efficiency of the process. This emission will cause environmental effects, e.g., global warming by reducing the heat radiation from the earth. When a substance does not exist in the reference environment, it must also react to reference substances in order to get in equilibrium with the environment. The reaction exergy at reference state equals the standard Gibbs energy change.

Exergy also appears as nuclear power. In fission this occurs by splitting heavy atoms and in fusion by putting together light atoms into heavy atoms. Since a part of the released energy in most cases appear as neutrinos, which can be regarded as invisible and non interactive, i.e., not able to convert to work, nuclear exergy may be written as

$$E = \Delta mc^2 - E_{\text{neutrino}} \qquad (20)$$

where c is the speed of light in vacuum, cf. equation (3) above. The energy of the neutrinos may sometime exceed 5% of the totally released energy, which gives an exergy factor of 0.95.

Exergy also appears as information, or information capacity. In 1905 Boltzmann [28] claimed that the free energy of the information that we actually possess (in contrast to the information we need to describe the system) is $kT \ln 2\, I$, where I are the information we have about the state of the system and k is the Boltzmann constant. The relation between exergy and information was given by equation (4) above [1]. Transformation of information from one system to another is often almost an entropy-free energy transfer. From information theory we have for the information or the information capacity I in binary units, i.e., bits

$$I = \frac{1}{\ln 2}\left(\sum_{j=1}^{\Omega} P_j \ln P_j - \sum_{j=1}^{\Omega} P_j^0 \ln P_j^0\right) \qquad (21)$$

where Ω is the number of possibilities, P^0 the probability at equilibrium, i.e., no knowledge, and P the probability when we know, i.e., have some information of the system.

It is important to observe that information or information capacity, does not necessary need to be meaningful from a human point of view. Information is here used as a measure of *order* or *structure*. Within science information is just as fundamental as energy and matter. By small amount of exergy as information, processes converting huge amounts of energy and matter can be controlled. The exergy carried as information is usually a very small part of the total exergy of any system. Thus, it ought to be treated as a resource of one's own, often named structural exergy [1]. This becomes obvious as we look into living matter or organisms, i.e., any single living plant, animal, bacterium or fungus, which will be further treated below. By this we have presented exergy in the form of energy, material and information. Next we will introduce the concepts of exergy efficiency and exergy flow diagrams.

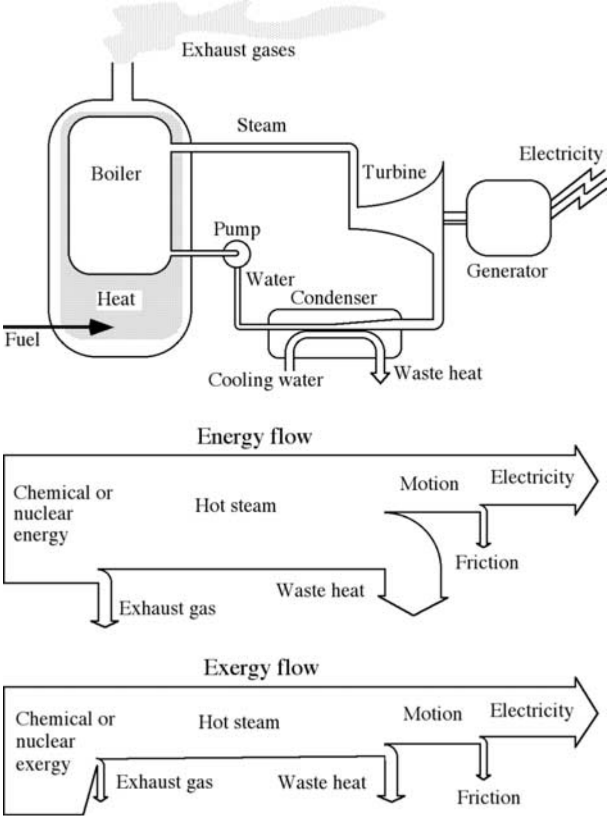

Figure 6. Energy and exergy flows through a condensing power plant.

For real processes the total exergy input always exceeds the total exergy output, this unbalance is due to exergy destruction, which is also named availability destruction, irreversibility, and lost work. The exergy output consists of the utilized output and the non-utilized output, i.e., exergy of waste E_{waste}. It is very important to distinguish between exergy destruction or irreversibility and exergy waste or unused exergy, i.e., exergy flow to the environment. Both represent exergy losses, but irreversibility has, by definition, no exergy and, thus, no environmental effects. Thus, in an exergy flow diagram, see the bottom flow diagram in *figure 6* that will be further explained below, irreversibilities are represented by narrowing the flows, whereas exergy wastes are the flows pointing downwards. However, due to high exergy losses from irreversibilities we need to put in more exergy to the process, in order to compensate for this loss, and this in turn may have an environmental impact, i.e., an indirect effect of exergy destruction.

The exergy destruction is related to the entropy production by

$$E_{\text{in}}^{\text{tot}} - E_{\text{out}}^{\text{tot}} = T_0 \Delta S^{\text{tot}} = \sum_i (E_{\text{in}} - E_{\text{out}})_i \qquad (22)$$

where $E_{\text{in}}^{\text{tot}}$ is the total exergy input, $E_{\text{out}}^{\text{tot}}$ is the total exergy output, ΔS^{tot} is the total entropy increase, and $(E_{\text{in}} - E_{\text{out}})_i$ is the exergy destruction in process i.

An exergy balance, by definition, only exists for reversible processes. Thus, for real processes, i.e., irreversible processes ($\Delta S^{\text{tot}} > 0$), exergy is never in balance, because the total exergy input always exceeds the total exergy output, i.e., $E_{\text{in}}^{\text{tot}} > E_{\text{out}}^{\text{tot}}$. Hence, it is misleading to speak of an exergy balance of real processes.

Possible process improvements are visualized by calculating the exergy losses, i.e., destruction and waste flows. In general, when the exergy loss is high, we should consider improving this part first. However, this ‘tackle the biggest loss first’ approach is not always appropriate. The reason is that, every part of the system depends more or less on every other part of the system so that an improvement in one part may cause increased losses in other parts, so that the total losses in the modified process may be larger than in the original process configuration. Therefore, the problem needs a more careful approach, which will be presented in Part 2 of this paper.

In engineering, flow diagrams are often used to describe the conversion of energy or exergy in a process, see *figure 6*. This figure shows a power plant, its main components and the energy and exergy flow diagrams of the plant. The exergy flow diagram shows losses both as destruction and emissions to the environment, which is important information for estimating environmental effects. It also gives a hint about the possibilities to improve the process and where to direct the efforts of improvement. In the energy flow diagram energy is always conserved, as stated by the first law of thermodynamics. The waste heat carries the largest amount of energy into the environment, far more than is carried by the exhaust gases. However, the temperature of the waste heat is close to ambient so the exergy is small. The exergy of the exhaust gas and the waste heat are comparable. In some cases the exergy of the exhaust gases even exceed those of the waste heat, as in the assumed coal power plant above. Energy and exergy losses from friction have little direct impact on the environment. Exergy is better related to the ecological effects than energy, which makes exergy flows better as ecological indicators.

In next section the exergy concept will be applied to the study of the life support system on the earth.

4. EXERGY IN NATURE

Exergy, which originates from the contrast between the sun and space, drives flows of energy and matter on the surface of the earth. There is more or less a balance between the inflow and the outflow of energy, besides a negligible capture of energy as fossil fuels and heat from geothermal energy. The average temperature on the earth’s surface is determined by, among other things, the amount of energy that radiates towards and away from the earth. Matter is transported via countless cycles through systems on the earth. The circulation periods for these cycles of matter can vary from fractions of seconds to billions of years. Examples of parts of such cycles can be nerve impulses in a cell and mining in society.

Figure 7. Flows of energy and matter on the earth are driven by exergy, as a consequence of the contrast between the sun and space.

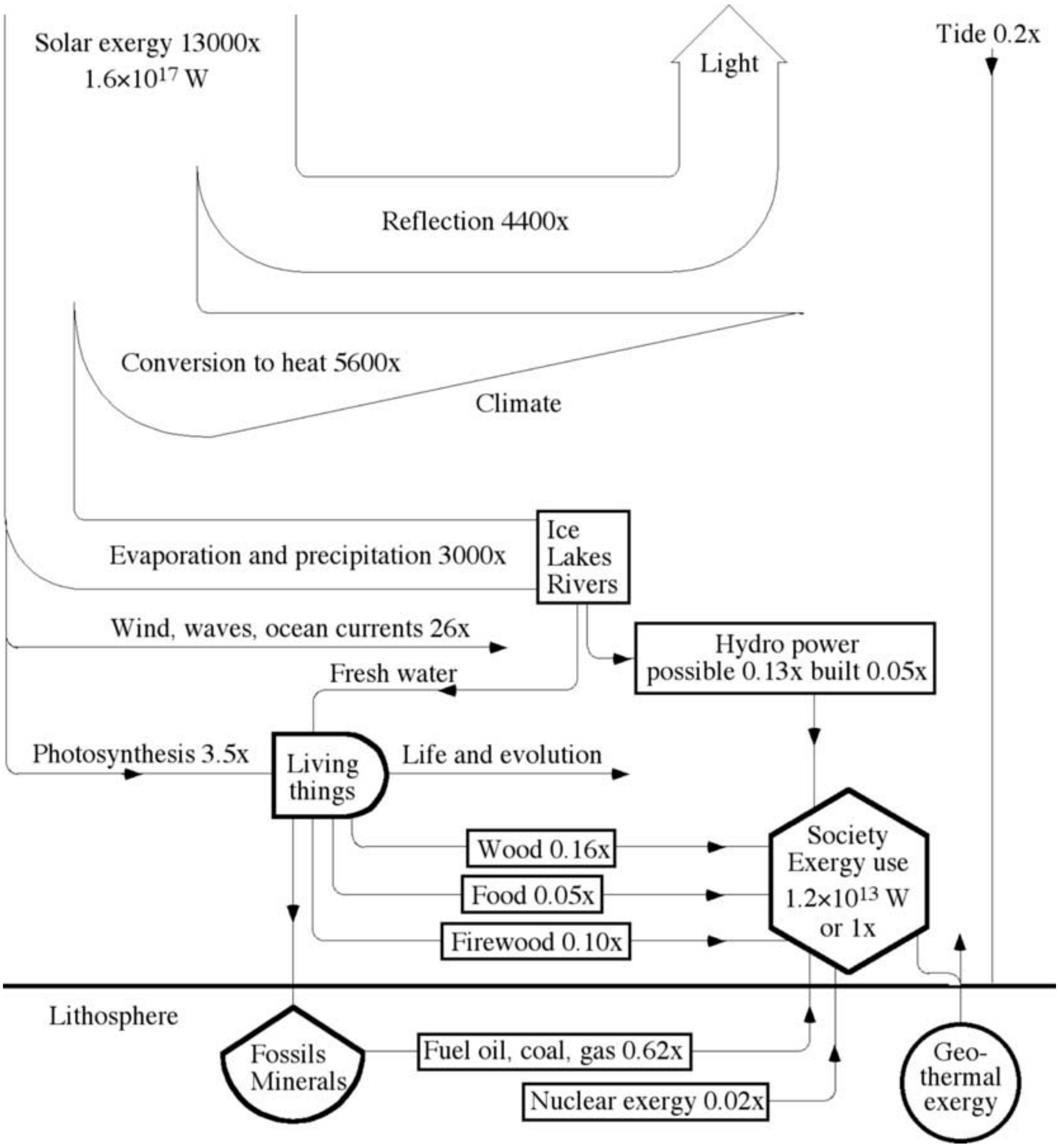

Figure 8. The exergy flows on the earth. All flows are indicated with relation to the exergy flow input to the society that is indicated 1 ×.

Energy as sunlight reaches the earth. A lot of it is reflected directly, and therefore it does not join in the conversion processes on the earth's surface. In *figure 7*, this reflected part is omitted and the inflowing sunlight is thus the net energy inflow, which is converted on the earth, and thereafter it leaves earth as thermal radiation. In *figure 7* the energy of the flow from sunlight to thermal radiation is conserved. The exergy of the sunlight is, however, consumed on the earth. The incoming solar radiation is relatively well ordered short-wave radiation and therefore has a high quality. The outgoing heat radiation is, however, relatively disordered long-wave and consequently of low quality. The whole of the earth can thus be seen as an immense machine working from the available exergy due to the contrast between the sun and the space. Due to this, all flows of energy and matter are carried forward through systems on the earth's surface, and life can be created and maintained.

The total exergy inflow to the earth from the sun/space system amounts to about 13 000 times the exergy use in the society, see *figure 8*. Almost all exergy used on the earth derives from the sun. A small fraction originates from the gravitational forces of the moon as tidal effects and from the interior of the earth as geothermal, fossil and nuclear exergy. About one forth of the sunlight is reflected back into space as light. The rest of the exergy is absorbed by the earth and is consequently for the most part gradually destroyed, but during this destruction it manages to drive the water/wind system and the life on the earth. The green plants convert exergy from sunlight into chemical exergy, via photosynthesis, see *figure 2*, above. The chemical exergy as biomass then passes through different food chains in the ecosystems. At every tropic level exergy is consumed and decomposition organisms live on the very lowest level in this food web. The exergy that cannot be utilized by these organisms instead form peat or sediment that gradually becomes stocks of oil or coal, i.e., deposits. Toxic matter is also being put away from the living system in these deposits of fossils and minerals. A fish being poisoned to death by a toxic substance will fall down to the sea floor together with the toxic substance, thus, removing it from the biosphere. Stocks in the form of living and dead organic matter on the earth, thus represent different forms of stored exergy. This storage of exergy builds up an enormous exergy potential, such as a clean environment and oxygen in the atmosphere, which is of crucial importance for the evolution of life into further diversity and complexity. We may conclude that natural evolution is forced by sunlight and is ‘self creating’, i.e., truly sustainable. The exergy use in the society originates to about 62% from fossil fuels, the rest is composed of mainly wood for construction and paper, firewood, food, hydro power and nuclear deposits. Thus, on the whole, the society’s exergy use is not sustainable, which will be further explained below by applying the exergy concept and the laws of nature to this use. The contribution to the society’s exergy use from solar, wind and wave power is too insignificant to appear in the diagram. The same accounts for the exergy in beasts of burden such as the ox and the donkey.

5. EXERGY USE IN THE SOCIETY

Resource use in the society may be classified, see *figure 9*. Natural resources, appear partly as natural flows and partly as stocks, which are divided into dead stocks or deposits and living stocks or funds [1]. Natural flows and funds are renewable, and deposits are non-renewable resources. From a technical and economical perspective only a part of the resources are regarded as reserves, see *figure 10*.

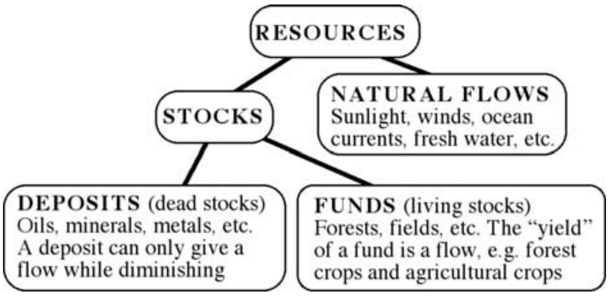

Figure 9. Classification of resources.

Resources cover a wide range, from hypothetical and speculative in the physical context to sub-marginal and unprofitable regarding the economic feasibility. However, reserves are only the known and profitable part of the resources, and in addition to this the sustainable reserves should also be specified, i.e., reserves that are ecologically acceptable. Ecologically acceptable parts of natural flows and funds could be regarded as sustainable reserves. However, deposits can not be regarded as sustainable reserves.

The exergy flow through the human society can be described according to this classification, see *figure 11*. The greater parts of the exergy requirements are seen to come from the terrestrial exergy stocks. Industrial society only uses a very small part of the direct exergy flow from the sun, e.g., within agriculture and forestry. In society there is on the whole, a continuous exergy loss. Some exergy flows, e.g., flows of metal from ores, increase their exergy when passing through society. However, other flows decrease their exergy all the more.

The limited amount of exergy stocks on the earth is indicated by a tank, that contains the funds and the deposits. As long as the levels are kept stable, i.e., the output of resources does not exceed the input from the sun and the biological processes, then we have a sustainable situation. However, if the level is dropping, i.e., the amount of stocks is depleting, then we have a non-sustainable situation. Obviously, this is the case for the industrial society that is depicted in *figure 1*. There is no or hardly any re-circulation of matter. Instead matter is being moved from deposits as minerals, or natural resources as they are named in economics, into the environment as emissions or waste dumped in nature (see *figure 12*). If the level of deposits is dropping, then substances will also be contaminated in the environment. As long as these substances are under control, i.e., within the sociosphere, see *figure 12*, this may not be a

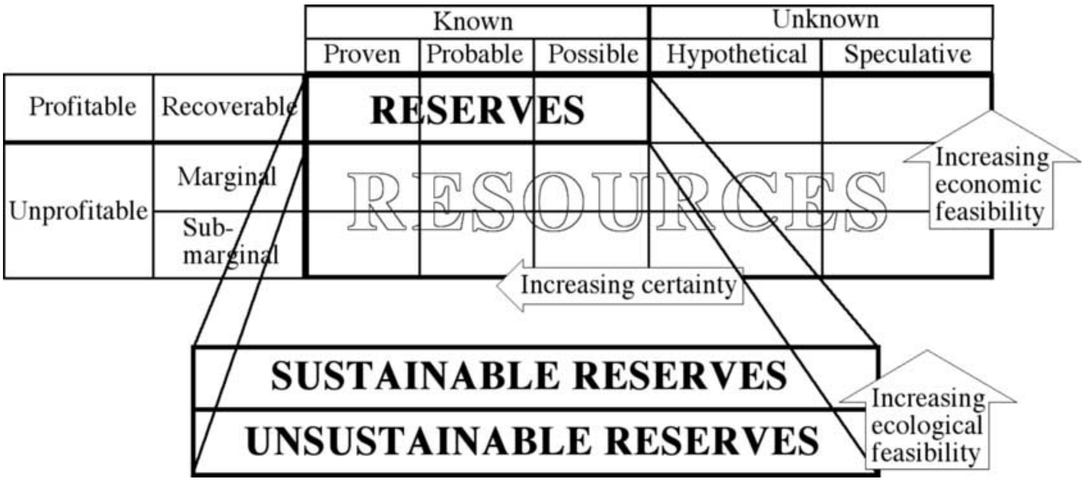

Figure 10. Definition of resources and reserves.

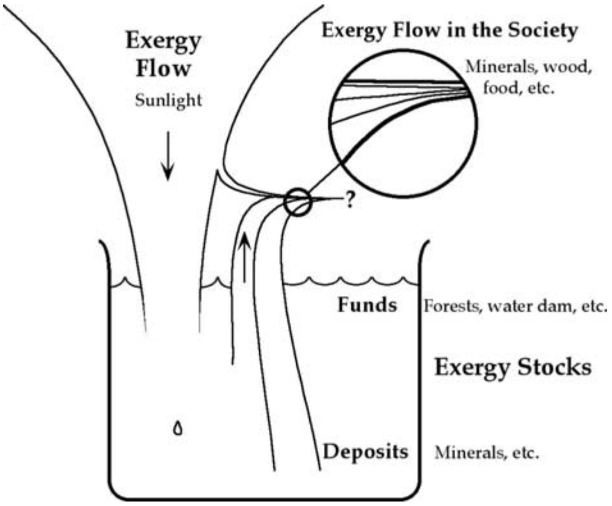

Figure 11. The exergy flow from the sun, and the exergy stocks on the earth create the resource base for human societies on the earth.

problem. Large amount of substances are accumulated in the sociosphere as constructions, e.g., buildings and machines, and, as long as these remain, their substances may not effect the environment. However, when they are allowed to decompose they may pose a serious threat, e.g., old nuclear, chemical, and biological arms that are not properly stored or destroyed. This also relates to harmful substances that are accumulated by a purification system. However, these buildings will not last forever. Sooner or later they will deteriorate and their substances will end up in the environment. Thus, environmental pollution is an inevitable consequence of the use of deposit resources. The depletion of the resource may not be the most serious problem, but rather the emission of toxic substances that will end up in the environment.

Natural evolution is an ongoing process that today is heavily affected by the emission of toxic substances from industrial society. In *figure 12* we see that the resource depletion and the environmental destruction are but two parts of the same problem, i.e., the use of deposits. In a closed system, nothing disappears and everything disperses, in accordance with the first and second laws of thermodynamics. Thus, all matter that is extracted from the lithosphere will sooner or later end up in the environment, as is indicated in *figure 12*. Presently, only nature offers the machinery to put these substances back into the lithosphere (see *figure 2* above). However, this will take nature millions of years, and in the meantime it may have serious impact on living conditions for mankind.

In economics the depletion of deposits is regarded as creation of value, when in physics or ecology it is the opposite. Thus, a better concept than sustainability to describe the difference between the natural system (*figure 2*) and the social system (*figure 1*) may be vitality [4]. The present use of resources in industrial society is obviously not sustainable, at least not for a very long time. The situation is similar to a colony of bacteria living from a limited resource. The population may increase exponentially for a short period but after that it collapses from the destruction of its own environment, i.e., its life support system is ruined.

However, the situation for the industrial society is even more dangerous, since we are also feeding new

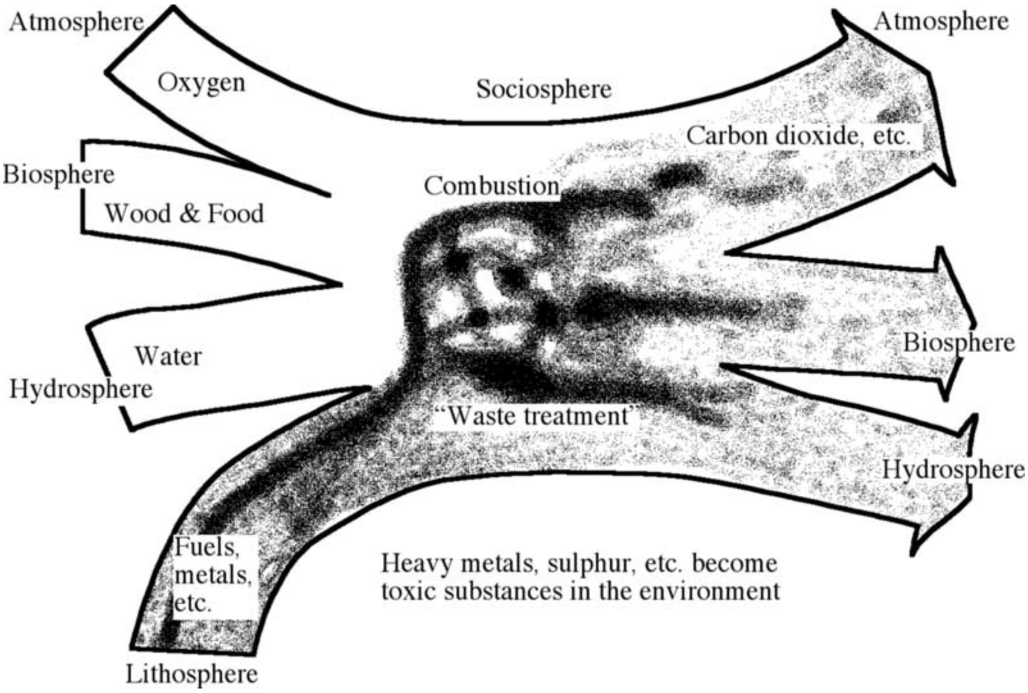

Figure 12. Resource depletion and environmental destruction are two sides of the same problem.

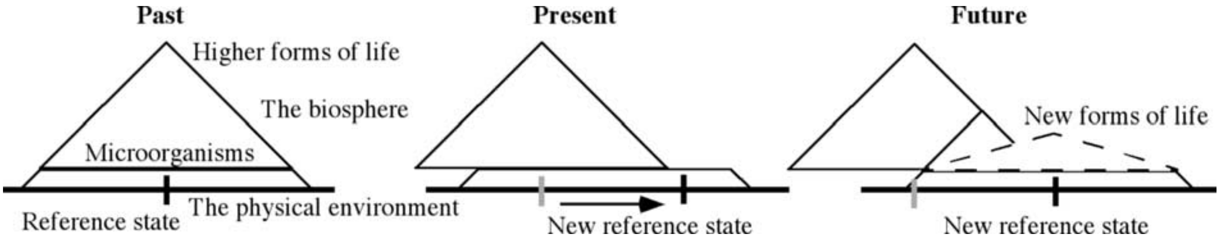

Figure 13. 'The Survival of the Fittest' or the driving forces behind the natural evolution [16].

microorganisms as we disperse huge amounts of toxic or exotic substances in the environment, see *figures 12* and *13*. Existing microorganisms, i.e., bacteria, fungi and viruses, provide the conditions on which present life is founded. Each human being carries about 2–3 kg of bacteria in the digestive system, and we all know the importance of keeping this system in balance. All forms of life are built on the existence of a specified mixture of certain microorganisms. These organisms are not only essential for our metabolism they are also essential for the immune defense. Penicillin is but one example of this. One single bacteria could in theory fill out the entire solar system within some weeks if it were able to grow without limitations. This describes the power of life that is under the control of nature, and the danger of interfering with these processes. However, by changing the physical environment in terms of chemical composition etc., we also create an environment that is unfavorable for existing microorganisms as well as higher forms of life. This may be recorded as a reduction in the number of species. However, the new physical environment that is offered will also encourage new forms of life to appear, initially by new microorganisms that are better fitted to the new conditions, e.g., bacteria that develop immunity to antibiotics. Later new insects or insects with new characteristics will appear, such as the malaria mosquito that is indifferent to DDT, and further on to mammals, e.g., rats that feed from rat poison. This is what Darwin expresses as 'the survival of the fittest'. Toxicity is an effect that often is transferred into the opposite by nature. A toxic substance is of course harmful for some organisms but at the same time it offers a new ecological niche that soon will be occupied by new organisms. This is a probable consequence of environmental pollution that unfortunately is seldom mentioned.

Thus, industrial society may nourish its own extinction by ruining the ecological foundations of human existence. It would be very naive to believe that these new microorganisms will be able to live in harmony with the present higher forms of life. The immediate signs of this are the appearance of new diseases and less resistance against existing diseases due to a weakened immune defense. Also the increasing rate of chronic allergy among children particularly in the developed countries may be a sign of this.

The human race will, of course, not stay forever anyhow. Just as other species have become extinct before us. Even more sophisticated and intelligent animals and organisms will most probably replace man in the future. This will be further discussed below. However, through the present environmental destruction, man and other organisms may become extinct much sooner than otherwise. The superiority of biological systems described above relates to the difference in information transfer techniques between biological and technical systems. This is of interest to study since it also reflects an important area of technology that still remains to be vastly developed.

Information must be stored and transported safely. To maintain this we must use redundancy, i.e., over-explicitness in codes and in copying, which implies access dissipation of energy to make the process irreversible, i.e., unambiguous. The explicitness in the process increases on behalf of the information capacity, i.e., a part of the available capacity must be used just to maintain exactness. In biological systems the transfer is supplemented with a continuous debugging or control of the transferred information. This is possible since the information is operated by living systems. In our increasingly computerized society, with the threat of computer viruses, this continuos control also becomes more important. Technological information systems work with macroscopic structures, e.g., print on a piece of paper, orientation of magnetic particles on a media, or positions of transistors in an electric circuit. Biological systems operate on a microscopic level, i.e., with the structure of molecules, e.g., the unique position of single atoms of the DNA (deoxyribonucleic acid) molecule. This makes biological system far more exergy efficient than technological systems.

In daily communication of information the exergy use is often very inefficient. When reading a book by lamplight the efficiency is about 10^{-20}, in a Power PC or Pentium microprocessor it is about 10^{-13}, and in the DNA-replication less than 10^{-2}. Thus, the information transfer efficiency of the most advanced microprocessor is still several magnitudes poorer than that of a bacteria.

In the biosphere solar exergy is converted into highly ordered structures in green plants. Exergy or information as ordered photons in sunlight is transferred into ordered structures in the living nature. The information is efficiently transferred in biological systems, far better than for technical systems, see *figure 14* [1]. The approximate areas of different electronic circuits, man's ear and eye, and protein biosynthesis are drawn in a logarithmic information rate (frequency)—power diagram. In 1956 Brillouin [29] showed that an elementary process in a circuit, such as a measurement, a storage or a logic operation, requires an exergy destruction which is large in relation to $kT \approx 4 \times 10^{-21}$ J (at room temperature). This is necessary to avoid thermal fluctuations, which are the cause of noise in electronic circuits, Brownian movement, etc. The ambient temperature, which causes these thermal fluctuations, is marked with a straight line in *figure 14*. Information transfer must ordinarily be far above this line to avoid serious disruption from thermal fluctuations. Protein biosynthesis is surprisingly close to this critical line. The ear and the eye occupy strikingly large areas in the diagram, covering many orders of magnitude. The sen-

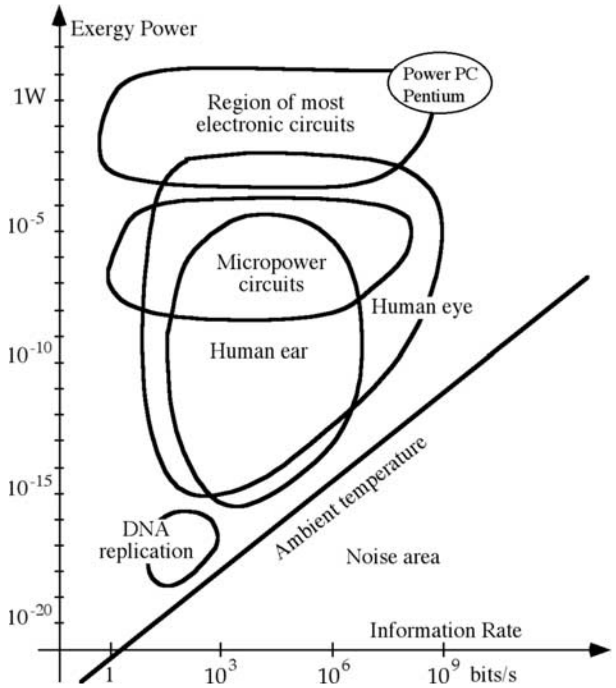

Figure 14. The information rate to power—diagram of some information transfer systems [1].

sitivity of the retina is such that the human eye functions near the quantum mechanical limit, i.e., only a few quanta are visible. Electronic circuits and micropower circuits are much less efficient than biological systems, and far away from the physical limits, which implies further important technical development and improvements can still be made. In this perspective today's most advanced computers are nothing but 'steam engines' in comparison with what will be available in the future.

Biological structures live by transforming exergy from one form to another. Solar exergy is transferred into complex organic structures that are directed by the information of the genes and if suitable living conditions are available. The information of the genes is transferred from generation to generation by DNA replication. When biological material, e.g., wood or cellulose, is used as a material, we benefit from the information stored as a structure, i.e., its structural exergy. This topic will be further elaborated in Part 2 of this paper.

Before closing this section we would also add some speculations by applying a longer time perspective to the present situation on the earth, see *figure 15*. At the creation of our solar system material substances and the laws of nature were present. At first matter was organized into a system able to reproduce itself. We call this life. Apparently nature has the machinery to create increasingly sophisticated and ordered structures operating in space and time. There seems to be a strategy acting behind the scene. So far it has led to the ability to think, i.e., to create awareness and a mind. This has given nature the ability to create imaginary structures such as culture, poetry and music, often carrying wisdom, harmony and love, and today we know that not only humans carry culture. The creation of exergy deposits on the earth is essential to the evolution that characterizes nature and life, since it establishes the necessary physical conditions. During billions of years nature has gone through an enormous change, which is so powerful that it has completely altered the living conditions on the earth, i.e., the life support system. This change has created a state far from thermodynamic equilibrium that can also be described in terms of exergy. The area in the bottom of *figure 15* indicates an estimation of the exergy stored as deposits on the earth, e.g., from the separation of carbon dioxide into deposits of carbon and oxygen in the atmosphere. However, the size of this area is magnified in order to be visible in the diagram. This build up of deposits is of vital importance for life and evolution on the earth. If all deposits were used up, then life as we know it today would completely disappear. Since, the situation would then be brought back to the state of the creation of our solar system, i.e., some 5 to 6 billions of years ago. Thus, from an ecological perspective the exergy of the deposits could be regarded as a measure of the value of the present living system. This could also be an indicator of environmental sustainability, since a reduction of this deposit of exergy, inevitably leads to a destruction of the life support system on the earth. The question marks in *figure 15* indicate that we are unable to predict or even imagine what kind of creatures will come after us. This is just as difficult as it would be for a bacterium to imagine a *Homo sapiens*.

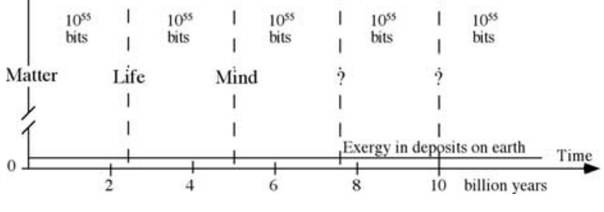

Figure 15. A small part of the exergy flow from the sun to the earth is stored as order on the earth, while matter is organized into life and further into the mind, and further into . . .? [16].

6. CONCLUSIONS

If there is no potential for work, i.e., no exergy, natural or artificial systems cannot work. This is a thermodynamic *dead* state, although energy still exists. Sustainable societies and ecosystems must maintain the potential of the sources they use to perform work. If a society consumes the exergy resources at a faster rate than they are renewed, it will not be sustainable. The present industrial society is obviously not sustainable and is facing a collapse. One may argue about details, such as how or when, but not that a culture based on resource depletion and environmental destruction is doomed. Probably mankind will not die from direct pollution but from new diseases related to new microorganisms that are better fitted in the increasingly polluted environment. The concept of exergy and global exergy accounting of natural resources offers a better understanding of nature as well as the problems behind the present ecological crises. Exergy is a well-defined concept that offers a unique opportunity to improve the resource use and to reduce the environmental destruction. We strongly recommend that exergy is adopted and applied in all disciplines handling these topics, e.g., engineering at large, environmental sciences and environmental economics. The amount of stored exergy on the earth as exergy deposits would probably be an ecologically sound indicator of sustainable development, since the natural living process acting on the earth is in a constant accumulation of exergy in deposits.

In the Part 2 of this paper we will present a number of suitable methods to be used and also give examples of environmental indicators related to the exergy concept.

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