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Conditions and tools in the design of energy conversion and management systems of a sustainable society

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Abstract

Mankind and especially engineering is today facing one of the most severe challenge ever. Present energy engineering leads to resource depletion and environmental destruction. Thus we need to develop an energy engineering in harmony with nature. This paper presents the conditions for this and in what way the exergy concept may contribute to this development.

Keywords: Industrial ecology; Sustainability; Resource use; Exergy; Environmental management

1. Introduction

This paper originates from earlier work [1]. The developed industrial society is built on a non-sustainable resource use (see Fig. 1). Resources as fossils and minerals from the lithosphere are used up in a one-way flow.

Production, in quotation mark, is the economical name of the extraction of these resources. Physically, this is no production. Deposited substances are released and spread in the environment, which is exactly the opposite to what is done by nature (see Fig. 2).

Natural processes, acting for billions of years, have built up these deposits in the lithosphere. By this, nature has also created the living conditions on earth, e.g. the access of oxygen in the atmosphere and the removal of toxic substances from the biosphere. Thus, when these substances are released the living conditions change. By changing the physical environment in terms of chemical composition etc., we create an environment that is unpleasant for existing microorganisms as well as higher forms of life. This is recorded as a reduction in the number of species. But, the new physical environment that is offered will also promote new forms of life to appear,

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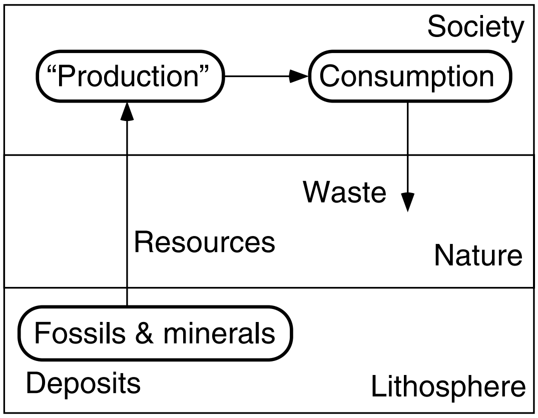

Fig. 1. Resource use in society.

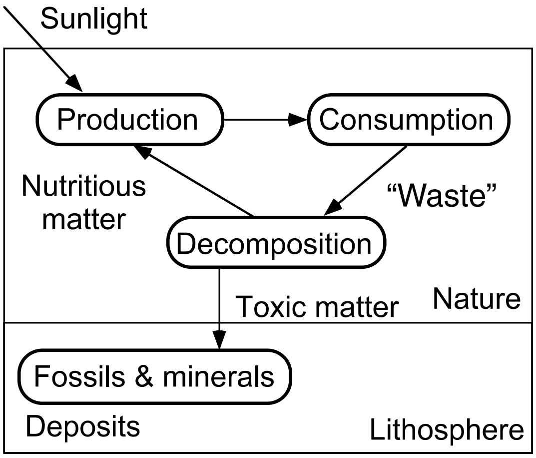

Fig. 2. Resource use in nature.

initially by new microorganisms, as bacteria that develop immunity of antibiotics. Later new insects will appear, as malaria mosquito that are indifferent to DDT, and further on to mammals as rats that feed from rat poison. This is what Darwin expresses as “the survival of the fittest”.

Thus, the situation is made clear. One may argue about details, such as how or when, but not that a culture based on resource depletion and environmental destruction is doomed. So, what must be done?

2. Exergy based tools and methods

The exergy concept brings new light to the problem or as it was stated by Goodstein [2] “In a world rapidly running out of fossil fuel, the second law of thermodynamics may well turn out to be the central scientific truth of the twenty-first century”. Below, is a short presentation of exergy related concepts and methods that are more and more applied, also into new fields.

2.1. Exergetics

Exergetics is a suitable generic term for the science of engineering that is based on the exergy concept. Exergy can be defined as work, i.e. ordered motion, or ability of work. This relates to the second law of thermodynamics that was initiated by the work of Carnot in 1824 [3].

2.1.1. Exergy losses

For real processes the exergy input E_{pr} always exceeds the exergy output E_{out}, this unbalance is due to irreversibilities, also named exergy destruction. The exergy output consists of the product E_{pr} and the waste, E_{waste}. Both exergy destruction and exergy waste represent exergy losses, but irreversibilities have, by definition, no exergy and, thus, no direct environmental effects. However, a large exergy destruction may imply a large use of exergy input that may cause environmental damage.

2.1.2. Exergy efficiencies

A simple definition of efficiency expresses all exergy input as used exergy, and all exergy output as utilized exergy.

$$\eta_{ex,1} = \frac{E_{out}}{E_{in}} \tag{1}$$

However, for most processes a part of the output is waste,

$$E_{out} = E_{pr} + E_{waste} \tag{2}$$

and the exergy efficiency $\eta_{ex,2}$ becomes

$$\eta_{ex,2} = \frac{E_{out} - E_{waste}}{E_{in}} = \frac{E_{pr}}{E_{in}} = \eta_{ex,1} - \frac{E_{waste}}{E_{in}} \tag{3}$$

Sometimes a part of the exergy goes through the system unaffected, i.e., the transit exergy E_{tr} (see Fig. 3). By deducting this exergy the efficiency $\eta_{ex,3}$ becomes

$$\eta_{ex,3} = \frac{E_{out} - E_{waste} - E_{tr}}{E_{in} - E_{tr}} = \frac{E_{pr} - E_{tr}}{E_{in} - E_{tr}} \tag{4}$$

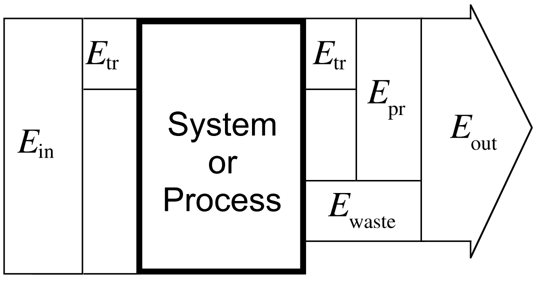

Fig. 3. The input and output of exergies for a system.

2.1.3. Exergy flow diagrams

The most efficient process is sometimes a matter of definition of efficiency. A better insight is offered by using exergy flow diagrams (see Fig. 3). From an exergy flow diagram can be learned:

- the exergy efficiencies of the various processes of a system,
- the different exergy inputs and outputs,
- where the various exergy flows come from and go to,
- the transit exergy,
- the exergy destruction in each processes.

2.1.4. Exergy or energy utility diagrams

A system is composed of a number of subsystems containing energy-donating and energy-accepting processes. The total energy is conserved for every subsystem, i.e.:

$$\sum \Delta H_k = 0, \quad k = 1, \ldots, \hat{k} \tag{5}$$

where $\hat{k}$ is the number of processes in the subsystem. Classified into energy donors and energy acceptors, the above equation becomes

$$\sum \Delta H_k^{\mathrm{ed}} + \sum \Delta H_k^{\mathrm{ea}} = 0 \tag{6}$$

where the superscript "ed" and "ea" mean energy donor and energy acceptor, respectively.

The second law of thermodynamics states that the total entropy is increased:

$$\sum \Delta S_k = \sum \Delta S_k^{\mathrm{ed}} + \sum \Delta S_k^{\mathrm{ea}} \geqslant 0 \tag{7}$$

Then exergy is lost in the process system:

$$\sum \Delta E_k = \sum \Delta H_k - T_0 \sum \Delta S_k = -T_0 \sum \Delta S_k \leqslant 0 \tag{8}$$

If we introduce the availability factor A [4]

$$A = \Delta E / \Delta H \tag{9}$$

Eq. (8) may be converted to:

$$-\sum \Delta E_k = \sum \Delta H_k^{\mathrm{ea}} \left(A_k^{\mathrm{ed}} - A_k^{\mathrm{ea}}\right) \tag{10}$$

When $\hat{k}$ goes to infinity, i.e., the subsystems are divided into infinitely small parts, the relation becomes:

$$-\int \mathrm{d}E = \int \left(A^{\mathrm{ed}} - A^{\mathrm{ea}}\right) \mathrm{d}H^{\mathrm{ea}} \tag{11}$$

Hence, by plotting A^{ed} and A^{ea} against H^{ea}, the exergy loss in the subsystem is represented by the area between A^{ed} and A^{ea}. This is call energy-utilization diagrams, EUD [5] and is a generalization and substantial extension of pinch technology [6].

2.1.5. Exergy analysis

To find all exergy used for a product, it is necessary to take all different inflows of exergy in the process into account. Exergy process analysis (see Fig. 4) focuses on a particular process or se-

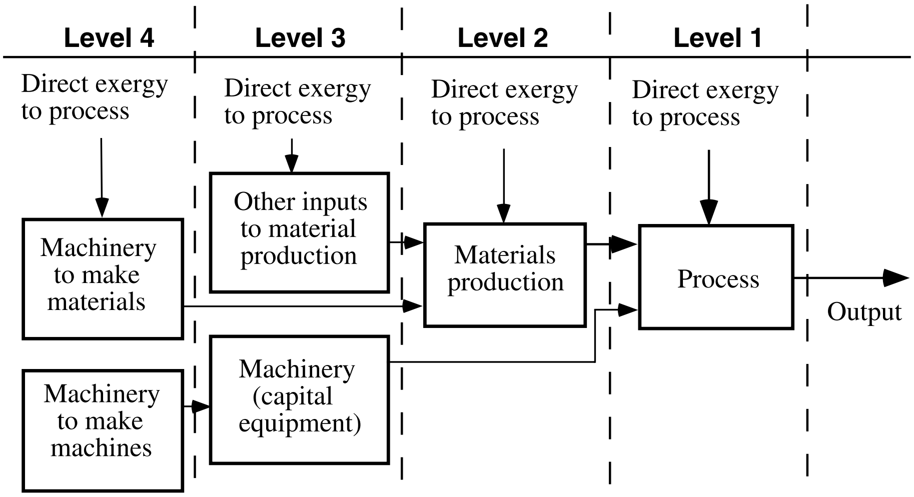

Fig. 4. The levels of an exergy process analysis.

quence of processes for making a specific final commodity and evaluates the total exergy use by summing the contributions from all the individual inputs, in a more or less detailed description of the production chain. This is similar to cumulative exergy consumption introduced by Szargut [7].

In a net-exergy analysis (see Fig. 5) all exergy being used, directly or indirectly, in the production of the product will be deducted from the exergy of the product to define the net exergy product.

Life cycle analysis or assessment (LCA) evaluates all in- and out-flows during the "life cycle" of a product with regard to the environmental impact. However, this multidimensional approach causes large problems when it comes to comparing different substances, and general agreements are crucial. Life cycle exergy analysis (LCEA) is a superior tool in this regard.

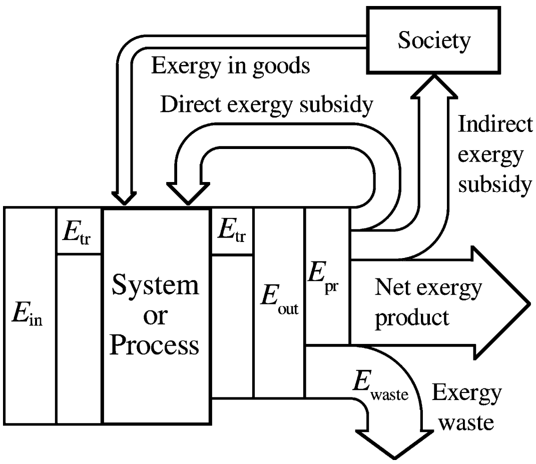

Fig. 5. Net-exergy analysis.

2.1.6. Life cycle exergy analysis

It is of essential important to move the resource use in the society towards sustainable resources. LCEA is a method to visualize this, by only accounting for the use of non-renewable resources, i.e. deposits as fossil fuel and minerals.

The exergy flow through a system, usually consists of three separate stages over time (see Fig. 6). Examples of these kind of systems are fossil-fueled energy plants. The exergy input used for construction, maintenance and clean up we call indirect exergy E_{indirect}. This exergy is different from the indirect exergy subsidy in Fig. 5. At first, we have the construction stage, $0 \leqslant t \leqslant t_{\text{start}}$. When a power plant is put into operation, it starts to deliver exergy power $\dot{E}_{\text{pr}}$, by converting the direct exergy power input $\dot{E}_{\text{in}}$. The direct exergy input only origins from deposits or non-renewable resources that will be ruined from the use and perhaps also bring harmful effects to the environment. This is always the situation in the use of deposits, e.g., metals and fossil fuels. Fig. 6 illustrate this case, and by definition we will never reach a situation where the total exergy input will be paid back, simply because the situation is powered by a depletion of resources. The net exergy output will always be less than zero, and in addition the system will generate depletion and environmental destruction.

Renewable resources are regarded as free and not accounted for. Nature uses these resources to build up its existence and development in a truly sustainable way, by storing a small amount of energy and exergy in deposits. Thus, the stored energy and exergy on the earth is increasing as evolution goes on. In the same way, a sustainable energy system must deliver more exergy than it consumes as deposits or non-renewable resources. This is possible only by using renewable resources, since these are regarded as free, and not included in the analysis. Examples of such of

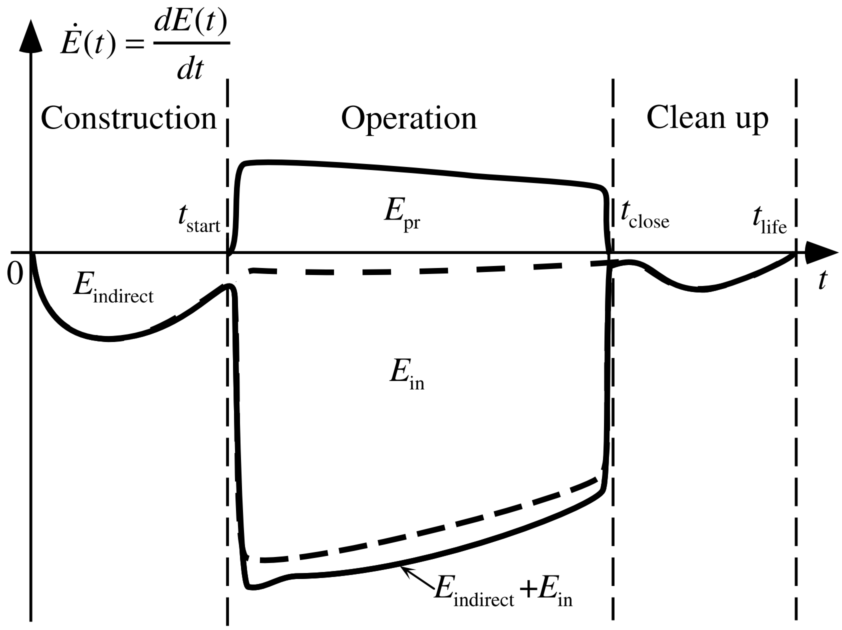

Fig. 6. Exergy use during a systems life cycle.

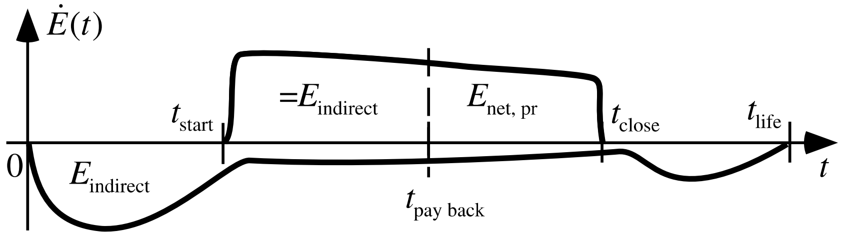

Fig. 7. Exergy use during a systems life cycle.

systems are solar and wind powered energy systems. Then, at time $t = t_{payback}$ the delivered exergy has covered up for the indirect exergy input, i.e. the use of deposits (see Fig. 7) i.e.

$$\int_{t_{start}}^{t_{payback}} \dot{E}_{pr}(t)\,dt = \int_0^{t_{life}} \dot{E}_{indirect}(t)\,dt = E_{indirect} \tag{12}$$

Thereafter, there will be a net exergy output from the plant, from the extraction of renewable resources, which will continue until it is closed down, at $t = t_{close}$. Then, we have to use exergy for clean up and restore the environment, which accounts for the last part of the indirect exergy input, i.e., $E_{indirect}$, which is already accounted for (see relation 12). By considering the total life cycle of the plant the net delivered exergy becomes:

$$E_{net,pr} = E_{pr} - E_{indirect} = \int_0^{t_{life}} \dot{E}(t)\,dt \tag{13}$$

These areas representing exergies are indicated in Fig. 7.

LCEA is very important in the design of sustainable systems, especially in the design of renewable energy systems. Sustainable engineering, ecological design, eco-technology or industrial ecology could be defined as systems which make use of renewable resources in such a way that the input of non-renewable resources will be paid back during its life time, i.e., $E_{pr} > E_{in}$. Thus, by using LCEA and distinguishing between renewable and non-renewable resources we have a method to define sustainable engineering. It should be noted that LCEA in its present form only accounts for exergy costs, however, in the future also monetary costs may be included.

2.2. Exergetics and economics

Exergy measures the physical value of a natural resource (energy, material and information). Thus, it is also related to the economic value, which reflects the usefulness or utility of a resource. Exergy can be applied to both macro and microeconomics [8].

2.2.1. Exergetics and macroeconomics

In order to encourage the use of renewable resources and to improve the resource use, an exergy tax could be introduced. In Fig. 8, inflow of non-renewable resources and waste, should be taxed by the amount of exergy. By a conversion factor, which has to be decided, the exergy is converted

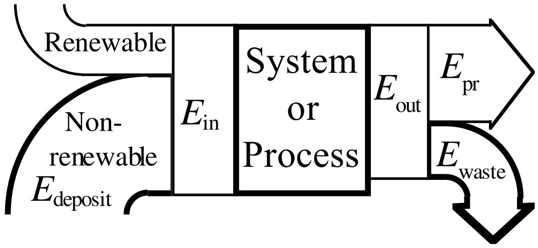

Fig. 8. Deposit and waste are subject to an exergy tax.

into monetary units. In addition to this, restrictions may be applied against toxicity and irreversible environmental effects.

To use exergy as base for tax has many advantages.

- The exergy can be calculated from given physical data for the substance and the environment, which could be decided by international agreements.
- The exergy is related to the utility of the extracted deposit, and to its physical or environmental value, i.e., the physical "cost" to produce the resource from the environment.
- Exergy is a measure of the physical value of the environmental stress that is created from the exergy waste when it ends up as waste in the environment.
- Exergy is always a positive value when we have a distinction from the natural environment.
- Exergy also offers an excellent internal efficiency concept to improve a system or process to meet these requirements in an optimal way.

This tax should be governed by an international organization, e.g., the United Nations, since the effects usually are global.

2.2.2. Exergetics and microeconomics

A system may be regarded from a physical and an economic environment, that are connected by cost relations, i.e., cost as a function of physical quantities (see Fig. 9). The physical environment is described by pressure P_α, temperature T_α, and a set of chemical potentials $\mu_{i,\sigma}$ of the appropriate substances i, and the economic environment by a set of reference prices of goods and interest rates. The aim is to minimize the life cycle cost (LCC):

$$\Phi_0 = \text{LCC} = \sum_{\text{lifetime}} C_{\text{pr}} = \sum_{\text{lifetime}} \left(C_{\text{in}} + C_{\text{labor}} + C_{\text{capital}} + C_{\text{tax}} - C_{\text{aid}}\right) \tag{14}$$

If we, by some reason, are not able to optimize the system, we may link cost to exergy by assuming a price of exergy, we call this exergy costing or thermoeconomic accounting.

Thermoeconomic accounting, was developed by Gaggioli [9], Evans and Tribus [10] by assigning economic values to the exergy flows.

When there are various in- and out-flows, the prices may vary. If the price per exergy unit does not vary too much, we can define an "average price". This method allows comparison of the economic cost of the exergy losses of a system. However, in a relative sense, this is always de-

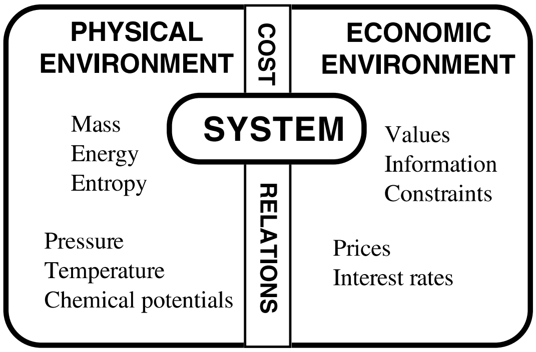

Fig. 9. The system in two environments.

pendent on the economic forces, and not on the real exergy values of the resources. Also waste flows represents an economic value, since, they will generate a cost for the society from its environmental effects. However, the question is a cost for whom?

Thermoeconomic accounting does not include consideration of internal system effects. It does not describe how the capital investments in one part on the system affect exergy losses in other parts of the system. In this method the exergy losses are figures not functions. However, this simple type of analysis sometimes gives ideas for, otherwise, not obvious improvements, and a good start of an optimization procedure.

Thermoeconomic optimization considers how the capital investments in one part of the system affect other parts of the system, thus optimizing the objective function, i.e., the LCC of the system or the product.

Usually, the design and operation of systems have many solutions, sometimes an infinite number. By optimizing the total system, we always find the best system under the given conditions. Some of the general engineering optimization methods could be applied to optimize specific design and operation aspects of a system. However, selecting the best solution among the entire set requires also engineering judgment, intuition and critical analysis.

The objective function Φ_0 should preferably be defined as a function of state parameters $\{x_j\}$, where $\{x_j\}$, is abbreviation for $x_1, x_2, \ldots, x_j, \ldots, x_n$, decision variables $\{y_k\}$, and decision parameters $\{z_l\}$, i.e.

$$\Phi_0 = \Phi_0(\{x_j\}, \{y_k\}, \{z_l\}) \tag{15}$$

where $j = 1, 2, \ldots, n$, $k = 1, 2, \ldots, m$, and $l = 1, 2, \ldots, r$.

The n state parameters are determined from the n equations of state:

$$\Phi_j(\{x_i\}, \{y_k\}, \{z_l\}) \tag{16}$$

where $j = 1, 2, \ldots, n$. Thus, the optimization is formulated as follows:

$$\text{Minimize } \Phi_0 = \Phi_0(\{x_i\}, \{y_k\}, \{z_l\}) \tag{17}$$

$$\text{Subject to } \Phi_j(\{x_i\}, \{y_k\}, \{z_l\}) \tag{18}$$

where $j = 1, 2, \ldots, n$ and the dimension of the decision space is $m + r$.

The optimization is preferably done by use of computer to calculate the value of the objective function Φ_0 and the marginal costs $\{\theta_k\}$ for every set of the decision variables $\{y_k\}$, where the decision parameter $\{z_l\}$ are set, according to:

$$\theta_k = \frac{\Delta\Phi_0}{\Delta y_k} \tag{19}$$

where $k = 1, 2, \ldots, m$. From these values a new set of variables $\{y_k\}$ is determined by using numerical methods. Thus, the system moves towards the nearest minimum from the given start values. However, if the problem is strongly non-linear common sense and insight into how the system works should be used together with sophisticated numerical optimization methods. We may also calculate the marginal cost of exergy for all parts of the system to find where exergy improvements are best paid off.

Optimization, in a general sense, involves the determination of a highest or lowest value over some range. In engineering we usually consider economic optimization, which usually means minimizing the cost of a given process or product, i.e., we need a well-defined objective function, as in relation 14. It is also important not to be misleading by a local optimum, which may occur for strongly non-linear relations. This is not to be mixed with improvement, which does not necessary mean that we optimize a system. Thus, the concept optimization must be used with caution.

2.3. Exergy in ecology

The interest of using exergy within ecology is presently increasing:

- In 1977 Wall outlined the basic ideas to incorporate the concept of exergy into the accounting of natural resources [11]. In this work both the use of energy and material resource in the society were treated in terms of exergy. Exergy analysis was proposed as a method to include the total exergy use of a product. The necessity to distinguish between resources originating from deposits, funds and natural flows were also pointed out in this work, as well as the need for an increasing concern for environment issues.
- Szargut [7,12] has suggested that "the index of cumulative consumption", i.e. loss of the exergy of deposits, can be redefined as the index of ecological costs.
- Wall [13] and Hirs [14] independently of each other have proposed an exergy tax. Wall computes it on the bases of the exergy of used deposit resources and emissions to the environment, whereas Hirs links it directly to the exergy losses.
- Ayres and Martinàs [15] state that in the case of a waste residual, exergy can 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 [16] have successfully introduced exergies of natural resources into the methodology of environmental LCA.
- Cornelissen [17] has developed a method called exergetic life cycle analysis, where the exergy destruction is used as a single criterion for the depletion of natural resources.
- A research project called "Exergy as an Environmental Indicator" is currently running at the University of California, Berkeley, (http://greenmfg.me.berkeley.edu/green/ResearchOverview/

Exergy.html) that is partly initiated by a pioneering work of Connelly in order to introduce exergy into the field of industrial ecology [18].

- Jørgensen and Nielsen [19] 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, by Blinge [20] is a development of LCA, which 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 [21]. From this study it is obvious that exergy will be further applied as a useful concept in the environmental field.
- Rosen and Dincer [22] just recently presented an application of exergy analysis to waste emissions. They conclude that exergy is a substantial contribution to the evaluationof environmental problems, however, further investigations are needed.

Figs. 1 and 2, above indicate what need to be done to make present engineering sustainable, and the studies above indicate that exergy is a useful concept in this regard.

3. Exergy use in the society

Fig. 10 is an exergy flow diagram of the resource use of the Japanese society in 1985 [23]. The situation is typical for an industrial society. The resource base is dominated by deposit resources, such as nuclear and chemical fuels, i.e., a non-sustainable situation. The exergy efficiencies in most conversions are very poor. The total efficiency is about 21% and for some conversions only about 5%. If we consider all steps in a resource chain the net output may be less than fractions of percentage, e.g., nuclear fuel to electricity to heat by short circuits. Thus, by applying exergy, the possibilities to improve the resource use are made obvious. This is an advantage of the exergy concept that needs to be further used.

The only sustainable resources are sunlight, hydro, forest and agricultural yields. Resources originating from funds such as biomass are sustainable only if they are used in a sustainable way, i.e. without endanger the ecological system. Thus, forest and agricultural industries are not necessarily sustainable. However, the yields from forest and agriculture are strongly depending on input of non-sustainable resources. Also, a large amount of the agricultural yield is imported. A sustainable Japan cannot be based on deposit resources. Thus, the present resource use must be completely changed. This is a must. By applying LCEA to the conversion processes of Fig. 10, the dependence on non-sustainable resources can be visualized for every product. This could be a first step towards a sustainable Japan.

4. Sustainable resources

Natural flows are sustainable, e.g. direct sunlight, wind and waves. 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 Fig. 11). Almost all exergy used on the earth derives from the sun. A small fraction origins

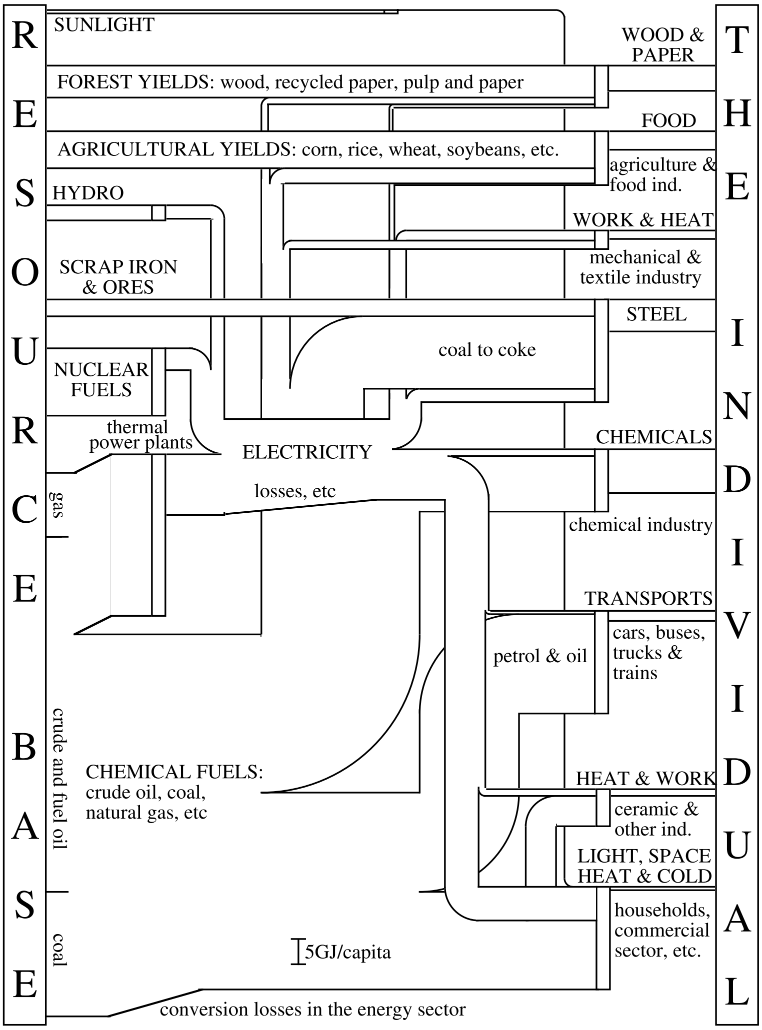

Fig. 10. The resource-conversion system in the Japanese society in 1985. The total input was about 18 EJ or 150 GJ/capita and the net output 3.8 EJ or 31 GJ/capita [21].

from the moon as tidal effects and from the interior of the earth as geothermal exergy. About one forth of the sunlight is reflected as light. The rest of the exergy is absorbed by the earth and is consequently gradually destroyed, but during this destruction it manages to drive the water/wind system and the life on earth. The green plants convert exergy from the sunlight into chemical exergy, via photosynthesis. The chemical exergy as biomass then passes through different food chains in the ecosystems. On every tropical level exergy is consumed and decomposition organisms live on the last level in this food chain. There exists no waste (see Fig. 2) above. This is not only a sustainable form of engineering, but also the driving force behind the ecological evolution. This form of engineering must be adopted by the society.

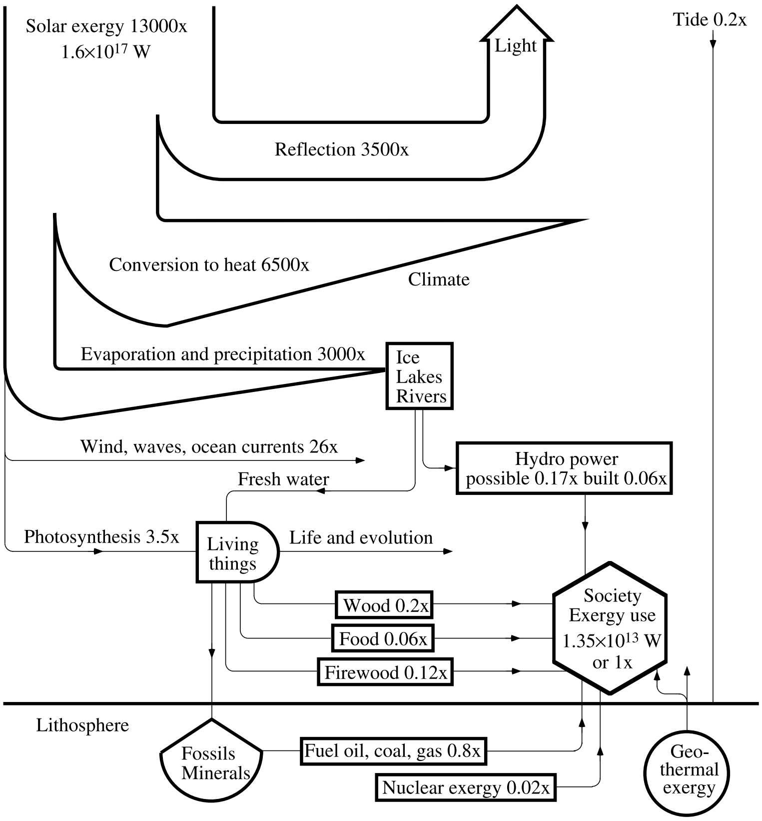

Fig. 11. The exergy flows on the earth.

5. Conclusions

Nothing disappears and everything disperse, these are two fundamental laws referring to the first and second laws of thermodynamics. These laws have a strong impact on our living conditions. The present resource use in the developed world implies resource depletion and an environmental destruction never seen before in the history of mankind, which also raises a question of morals [24].

From ecological point of view, the present resource use in the society is a non-sustainable situation. Deposits are exploited, used and become waste in a one-way flow. Instead we need to develop a sustainable engineering, similar to what is practiced by nature.

Exergy clarifies the situation by exposing the losses of a process and the emissions to the environment. The exergy concept puts a number to these flows, which are to be minimized in order to meet sustainable conditions. Thus, exergy is a suitable and necessary concept in the development of a sustainable society, and future research of exergy and its applications must be further directed towards the development of a sustainable society.

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