ON EXERGETICS, ECONOMICS AND OPTIMIZATION OF TECHNICAL PROCESSES TO MEET ENVIRONMENTAL CONDITIONS

Mei Gong and Göran Wall
Exergy Studies
Solhemsgatan 46, SE-431 44 Mölndal
Sweden
Phone/Fax: +46-31-877579, Email: gw@exergy.se, WWW: http://exergy.se

Presented at

TAIES'97
International Conference on **T**hermodynamic **A**nalysis and **I**mprovement of **E**nergy **S**ystems
Beijing, China, June 10-13, 1997

published in
Ruixian Cai, et al. Eds., "Thermodynamic Analysis and Improvement of Energy Systems," pp. 453-460, Beijing World, Chinese Society of Engineering Thermophysics and American Society of Mechanical Engineers(1997)

ISBN 7-5062-3264-Z

ABSTRACT

This paper introduces and clarifies important concepts in the development of a sustainable engineering.

An engineer designing a system is expected to aim for the highest possible technical efficiency at a minimum cost under the prevailing technical, economic and legal conditions, but also with regard to ethical, ecological and social consequences. Exergy is a concept that makes this work a great deal easier. Thus, exergetics offers a unique insight where losses and possible improvements can be determined, and Life Cycle Exergy Analysis (LCEA) is suggested as a method to better meet environmental conditions.

Exergy is also a useful concept in economics. In macroeconomics exergy offers a way to evaluate resource depletion and environmental destruction by means of an exergy tax. In microeconomics exergy has fruitfully been combined with cost-benefit analysis to improve the design. By minimizing Life Cycle Cost (LCC) we find the best system due to the prevailing economic conditions, and by minimizing the exergy losses, we also minimize environmental effects.

INTRODUCTION

Designing efficient and cost effective systems, which also meet environmental conditions, is one of the foremost challenges that engineers face. In the world with finite natural resources and large energy demands, it becomes increasingly important to understand the mechanisms which degrade energy and resources and to develop systematic approaches for improving systems and thus also reducing the impact on the environment. Exergetics combined with economics, both macro- and microeconomics, represents powerful tools for the systematic study and optimization of systems. Exergetics and microeconomics forms the basis of thermoeconomics (Evan and Tribus, 1962), which is also named exergoeconomics (Bejan et al, 1996) and exergonomics (Yantovskii, 1994). The concept of utility is a central concept in macroeconomics. Utility is also closely related to exergy, and an exergy tax is an example of how exergy could be introduced into macroeconomics.

Optimization pervades the fields of science, engineering, and business, which is concerned with finding the best system among the entire set by efficient quantitative methods. Computing makes the selection feasible and cost efficient. But to employ them requires, firstly critical analysis of the process or design, secondly insight as to what the appropriate performance objectives are, i.e., what is to be accomplished, and thirdly use of past experience, sometimes called "engineering judgment."

However, the design is much more than using proper tools and performing a correct optimization. In a real system design consideration for environmental, social and ethical consequences must also be taken. Good design methods should also make maximum use of the designer's skills, knowledge, and experience. (Sama, 1995) In addition, a designer should also have a basic knowledge in ecology and sociology, as well as ethics and morals. (Wall, 1995)

When constructing a system, the goal is to attain the highest possible technical efficiency at the lowest cost within the existing technical, economical and legal constrains. The analysis also includes different operating points (temperatures, pressures, etc.), configurations (components, flow charts, etc.), purpose (dual purpose, use of waste streams, etc.), and environments (global or local environment, new prices, etc.).

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 engineering judgment, intuition and critical analysis. "It is much more important to be able to survey the set of possible systems approximately than to examine the wrong system exactly. It is better to be approximately right than precisely wrong." (Tribus and El-Sayed, 1982)

Table 1 Energy versus Exergy

Energy	Exergy
The first law of thermodynamics	The second law of thermodynamics
Nothing disappears.	Everything disperse.
Energy is motion or ability to produce motion.	Exergy is work[1] or ability to produce work.
$\Delta Q = \Delta U + \Delta W$ (1) where: ΔQ is the total heat supplied to the system, ΔU is the total increase in the internal energy U of the system, ΔW is the total increase in the external energy of the system or the total work done by the system.	$E = T_0(S_{eq}^{tot} - S^{tot})$ (2)[2] where: E is exergy, T_0 is the temperature of the environment, S_{eq}^{tot} is the entropy of the total system, i.e. the system and the environment when the system is in equilibrium with the environment, S^{tot} is the entropy of the total system at a certain appropriate deviation from equilibrium.
$E = mc^2$ (3)[3] Energy and matter m is "the same thing." Everything is energy.	$E = k \ln 2\, T_0 I$ (4)[4] Exergy 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 only conserved or in balance for a reversible process, but partly consumed 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 quality and quantity.[5]

[1] Work is ordered motion.

[2] This equation is known as the *Gouy-Stodola theorem*. (Gouy, 1889 and Stodola, 1898) G. Gouy and A. Stodola discovered, independently 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 of thermal processes.

[3] This is the well known formula, stated by Einstein, however, where E here is energy and not to be mixed with E otherwise used for exergy in this paper, m is mass, c is the speed of light, which is equal to 3×10^8 [m/s].

[4] Thus $k\ln2T_0 \approx 2.9\times10^{-21}$ J is the amount of exergy of one bit of information at room temperature. And I is information, or information capacity [bit].

[5] Entropy, or negentropy can be regarded as a measure of quality.

This paper compares the concept of energy and exergy, introduces different ways to define exergy efficiency, and distinguishes between exergy destruction caused by irreversibility and exergy waste due to unused exergy. Net-exergy analysis or Life Cycle Exergy Analysis (LCEA) as methods of calculating the total resource use for a specific product or service will be presented, as well as the application of exergetics in micro- and macroeconomics. Also the difference between optimization and improvement will be clarified.

EXERGETICS

Thermodynamics provides the concepts of temperature, pressure, heat, work, energy, entropy and four laws of thermodynamics. Thermodynamics only treats reversible processes, i.e. processes with no direction, for systems in equilibrium states. Even though, thermodynamics is one of the most useful part of physics in engineering.

First law, i.e. energy analysis, 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 of thermodynamics shows that, for some energy forms, only a part of the energy is convertible to work, i.e. the exergy. However, still this is not recognized by the engineering society at large. "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." (Goodstein, 1994) In Table 1 we have summarized the main differences between energy and exergy.

Exergy Losses

For a real process the exergy input always exceeds the exergy output, this unbalance is due to irreversibilities, which we name exergy destruction ΔE. The exergy output consists of the utilized output and the non-utilized output, i.e. exergy of waste output. This latter part we entitle the exergy waste E_{waste}. It is very important to distinguish between exergy destruction caused by irreversibilities and exergy waste due to unused exergy, i.e. exergy flow to the environment. Both represent exergy losses, but irreversibilities have, by definition, no exergy and no environment effects.

The exergy destruction ΔE is related to the entropy generation by

$$\Delta E = T_0 \Delta S^{tot} = E_{in}^{tot} - E_{out}^{tot} = \sum_i \Delta E_i \qquad (5)$$

where ΔS^{tot} is the total entropy increase, E_{in}^{tot} is the total input exergy, E_{out}^{tot} is the total output exergy, and ΔE_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 ($\Delta S^{tot} > 0$), exergy is never in balance, because the total exergy input always exceeds the total exergy output, i.e. $E_{in}^{tot} > E_{out}^{tot}$. Hence, it is misleading to talk about an exergy balance for real processes.

In the literature, exergy destruction is commonly referred to as *availability destruction*, *irreversibility*, and *lost work*.

By calculating the exergy loss, i.e. destruction and waste, we can visualize possible process improvements. In general, when the exergy loss is high, we should consider to improve 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 on each other 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 equal or even larger than in the original process configuration. Therefore, the problem needs a more carefully approach, which we will discuss below.

Exergy Efficiency and Exergy Flow Diagrams

Exergy efficiency[6] is usually defined, as utilized exergy divided by used exergy. This must be a number between 0 and 1, since all real processes involves exergy destruction. This is in distinction to energy efficiency which may well exceed 1. However, there are several ways to define the utilized exergy and used exergy. We also want to mention that exergy efficiency could also be defined as utilized exergy divided by the exergy which is theoretically possible to utilize. (Wall, 1977)

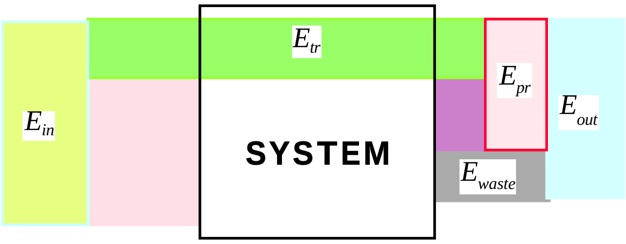

Figure 1 The input and output of exergies for a system.

The definition introduced by Grassman (1950) expresses all exergy input as used exergy, and all exergy output as utilized exergy. So the exergy efficiency $\eta_{ex,1}$ becomes

$$\eta_{ex,1} = \frac{E_{out}}{E_{in}} = 1 - \frac{\Delta E}{E_{in}} \tag{6}$$

where we have added the definition of exergy destruction ΔE from above.

However, this efficiency does not always provide an adequate characterization of the thermodynamic efficiency of processes, such as heat transfer, separation, expansion etc. Often, there exists a part of the output exergy which is unused, i. e. an exergy waste E_{waste} to the environment. Thus, the utilized exergy is given by $E_{out} - E_{waste}$, which we call the exergy product E_{pr}, i.e.

$$E_{out} = E_{pr} + E_{waste} \tag{7}$$

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

$$\eta_{ex,2} = \frac{E_{out} - E_{waste}}{E_{in}} = \frac{E_{pr}}{E_{in}} = \eta_{ex,1} - \frac{E_{waste}}{E_{in}} \tag{8}$$

Sometimes a part of the exergy going through the system is unaffected. This part of the exergy has been named the transiting exergy E_{tr}. (Kostenko, 1983, and Brodyansky et al., 1994), see Fig. 1 and Eq. 9.

If the transiting exergy E_{tr} is deducted from both the input and the output exergy (or rather from exergy product), the exergy efficiency $\eta_{ex,3}$ becomes

$$\eta_{ex,3} = \frac{E_{out} - E_{waste} - E_{tr}}{E_{in} - E_{tr}} = \frac{E_{pr} - E_{tr}}{E_{in} - E_{tr}} \tag{9}$$

Due to the difficulties to sometimes calculate the transiting exergy and its lack of recognition, we support to use the exergy efficiency $\eta_{ex,2}$, i.e.

$$\eta_{ex} = \eta_{ex,2} = \frac{E_{out} - E_{waste}}{E_{in}} = \frac{E_{pr}}{E_{in}} \tag{10}$$

Let us compare these definitions by applying them to a system with two different processes A and B, see Fig. 2. The exergy efficiencies are for process A: $\eta_{ex,2}$=91% and $\eta_{ex,3}$=10%, and for process B: $\eta_{ex,2} = \eta_{ex,3}$=50%. Thus, which is the most efficient process is a matter of definition of efficiency. However, if we instead use the diagrams, we can see that the exergy destruction of process A is larger than that of process B, 9 versus 5, thus, process A probably should be improved first.

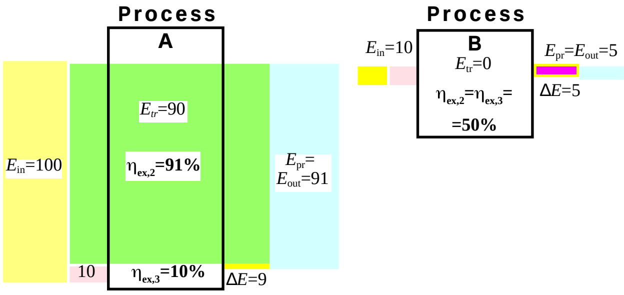

Figure 2 Comparing the use of efficiencies $\eta_{ex,2}$ and $\eta_{ex,3}$ with exergy flow (Sankey-Grassman diagrams) of two processes A and B in a system

From this comparison we see that a better insight is offered by using exergy flow diagrams. From an exergy flow diagram can be learned not only what the exergy efficiencies of the various processes of a system are, but also what input and output the exergies refer to, where the various exergy flows come from and go to, which part is transiting exergy, and how much exergy is destroyed of each processes. "Again, ambiguity is eliminated if a Sankey diagram is used instead of a ratio to summarize an energy account." (Spreng, 1988)

Exergy flow diagrams may also include the total exergy use for a product or service both in the production and in the waste treatment as well as in the use of the product or service. Thus, we have to consider the time, i.e. both the history and the

6 Also called second law efficiency, effectiveness, or rational efficiency

future of our activity. We name this **Life Cycle Exergy Analysis** (LCEA).

Life Cycle Exergy Analysis

To find all exergy which is used in the production, it is necessary to take all different inflows of exergy in the process into account. In 1974, a conference was held by the International Federation of Institutes for Advanced Studies (IFIAS) at which this type of budgeting was denoted **energy analysis**, and Gibbs free energy was chosen as a unit of measure. (IFIAS, 1974).

There are basically three different methods used to perform an energy analysis, these methods are process, statistical and input-output analysis. (Chapman and Roberts, 1983) The latter is based on an input-output table as a matrix representation of an economy. Each industry sector is represented by a row and column in the matrix. The main advantage of this method is that it can quickly provide a comprehensive analysis of an entire economy, and the main disadvantages results from the use of financial statistics and from the degree of aggregation in the table. In order to obtain a more detailed disaggregation than used in input-output tables it may be sufficient to make use of the more detailed statistics from which input-output tables are usually compiled. The method is called statistical analysis, which is basically a longhand version of input-output analysis. This method has two advantages over the input-output method: (1) it can achieve a more detail analysis, and (2) it can usually be executed directly in physical units, thus avoiding errors due to preferential pricing, price fluctuations, etc. However, its disadvantage compared to the input-output method is that the computations usually have to be done manually. Process analysis, see Fig. 3, focuses on a particular process or sequence of processes for making a specific final commodity and evaluates the total energy use by summing the contributions from all the individual inputs, in an more or less detailed description of the production chain. Exergy could easily be incorporated into the process analysis to form an **exergy analysis**, see Fig. 3.

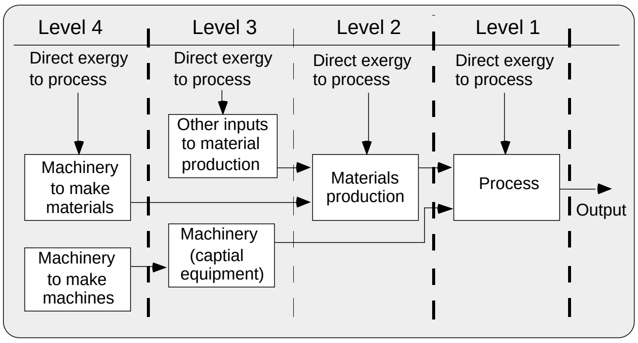

Figure 3 The levels of process analysis as described at the IFIAS workshop, with the addition of exergy. (IFIAS, 1974)

Later the more clarifying name **net-energy analysis** has been used to for this kind of analysis. (Spreng, 1988) This method is described in terms of exergy in Fig. 4. As we see, 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.

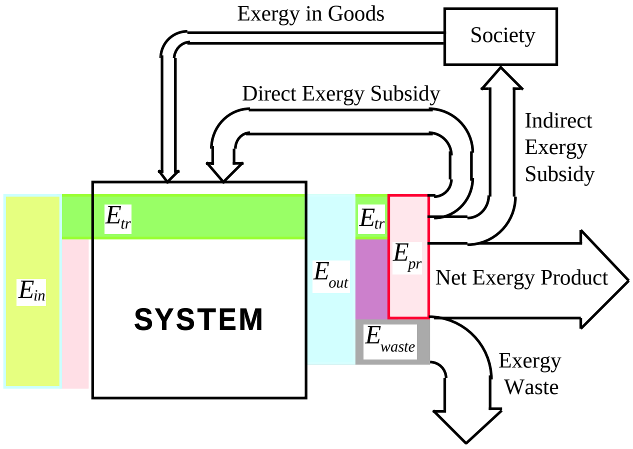

Figure 4 Net-exergy analysis.

Szargut and Morris (1987) have introduced the concept of **cumulative exergy consumption** to express the sum of the exergy of natural resources consumed in all steps of a production process.

Life Cycle Analysis or Assessment (LCA) is a method that evaluates all in- and outflows during the "life cycle" of a good or service with regard to the environmental impact. LCA has attracted a lot of attention, and is very similar to the methods presented above except that it is not restricted to energy or exergy. However, this multidimensional approach causes large problems when it comes to comparing different substances, and general agreements are crucial. Furthermore, LCA is a poor tool in the design of a system since it can only evaluate already proposed systems. Meanwhile, we suggest that **Life Cycle Exergy Analysis** (LCEA), which we present below, is used. Let us first classify resources, see Fig. 5. Natural resources, appear partly as *natural flows* and partly as *stocks*, which are divided into *dead stocks* or *deposits* and *living stocks* or *funds*. Natural flows and funds are renewable, and deposits are non-renewable resources.

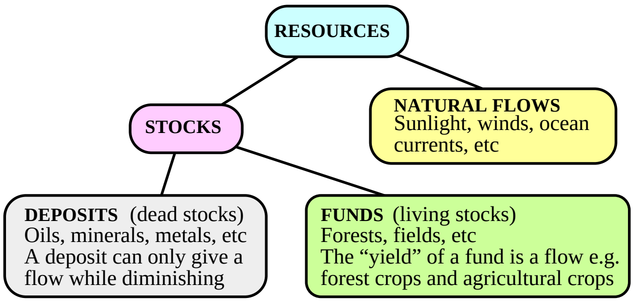

Figure 5 A classification of resources (Wall, 1997).

The exergy flow through an energy system, usually consists of three separate stages over time, see Fig. 6. At first, we have the construction stage where exergy is used to build a plant and put it into operation. During this stage, $0 \le t \le t_{start}$, exergy is spent of which some is accumulated or stored in materials. e.g.

in metals etc. The exergy input used for construction, maintenance and clean up we call indirect exergy E_{indirect}. When the power plant is put into operation, it starts to deliver exergy power $\dot{E}_{\text{pr}}$, by converting the direct exergy power input $\dot{E}_{\text{in}}$. Let us now look at two cases, (1) the direct exergy is a renewable resource, and (2) the direct exergy is a non-renewable resources.

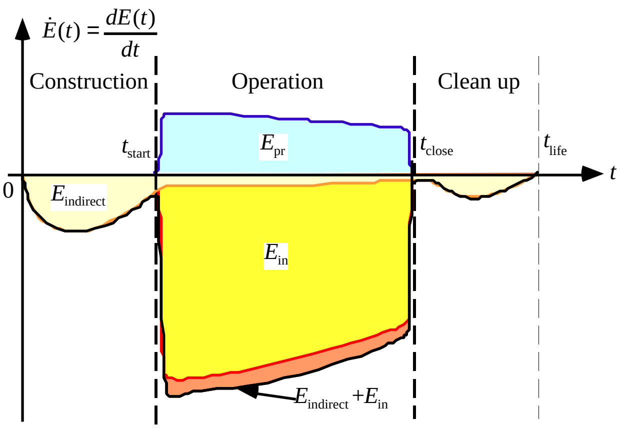

Figure 6 Exergy input and output during a systems life cycle.

In the first case, we can disregard the direct exergy input, since we use exergy originating from natural flows, like solar, or funds. Then, at time $t = t_{\text{pay back}}$ the delivered exergy has covered up for the indirect exergy input, see Fig. 7, i.e.

$$\int_{t_{\text{start}}}^{t_{\text{pay back}}} \dot{E}_{\text{pr}}(t)dt = \int_{0}^{t_{\text{life}}} \dot{E}_{\text{indirect}}(t)dt = E_{\text{indirect}} \tag{11}$$

Thereafter, there will be a net exergy output from the plant, which will continue until it is closed down, at $t = t_{\text{close}}$. 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 paid pack for. By considering the total life cycle of the plant the net delivered exergy becomes:

$$E_{\text{pr, net}} = E_{\text{pr}} - E_{\text{indirect}} = \int_{0}^{t_{\text{life}}} \dot{E}(t)dt \tag{12}$$

These areas representing exergies are indicated in Fig. 7.

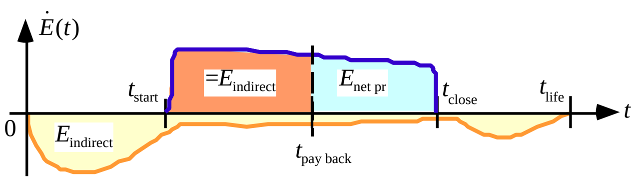

Figure 7 Exergy input and output during a systems life cycle.

In the next case, we assume that all direct exergy input must be considered, i.e. we use a deposit or non-renewable resource which will be ruined from the use and perhaps also bring harmful effects to the environment resource. This is always the situation in the use of non-renewable or deposit resources like minerals and fossil, e.g. metals and fossil fuels. Figure 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, we have

$$E_{\text{pr}} < E_{\text{in}} \tag{13}$$

Life cycle exergy analysis is very important in the design of sustainable systems, especially in the design of renewable energy systems. Assume a solar panel made of mainly aluminum and glass is used for production of hot water. Then, it is not obvious that the exergy being spend in the production of this unit ever will be paid back during its use, i.e. it might be a misuse of resources rather than a renewable resource use. Life cycle exergy analysis should therefor be done in the design of such systems.

Sustainable engineering should 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. Thus, by using LCEA and distinguishing between renewable and non-renewable resources we have a method to define sustainable engineering.

ECONOMIC AND EXERGETICS

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 of a resource.

Exergy can be applied to both macro- and microeconomics, and so far it has mainly been used in microeconomics, e.g. thermoeconomics. However, the concept of utility used in macroeconomics is closely related to exergy, and with an increasing interest from economist for the environment, e.g. environmental and ecological economics, we expect that exergy will also be used in macroeconomics in the near future. The introduction of an exergy tax, see below, is but one example.

Some economists consider natural resources as any other factor of production. Others feel, by considering the value of the natural environment, that natural resources has a special meaning in economics. Boulding (1966) characterizes these two views as the cowboy economy and spaceman economy:

> "In the cowboy economy, consumption is regarded as a good thing and production likewise; … , in the spaceman economy, throughput is … something to be minimized rather than maximized. … The essential measure of the success of the economy is not production and consumption at all, but the nature, extent, quality, and complexity of the total capital stock; included in this state of the system are the human bodies and minds."

It is obvious that Boulding is referring to something that is related to exergy and an exergy tax.

Macroeconomics and Exergetics — Exergy Tax

The world faces a lack of deposit natural resources and an environmental destruction. In order to encourage the use of renewable resource and to improve the resource use, an exergy tax could be introduced. (Wall, 1993) In Fig. 8 we have divided the resource inflow into two parts — renewable and non-renewable resources which should be taxed. Also waste products, i.e. exergy waste, should be taxed by the amount of exergy released since this is related to the environmental impact. However, in addition to this, one must, of course, also consider toxicity and other indirect environmental effects, and in the case of irreversible environmental damage, a tax is not suitable, instead restrictions must be considered.

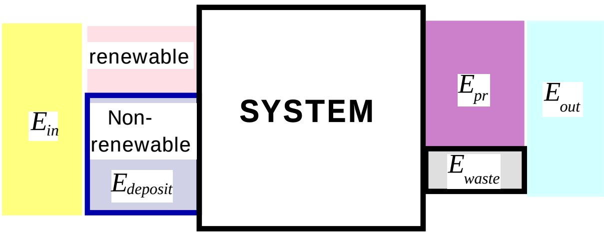

Figure 8 Exergy taxed in the system. Outlined part should be taxed.

In economics systems always have a monetary balance, see Eq. 14 and Fig. 9, where we have added exergy tax and aid.

$$C_{in} + C_{labor} + C_{capital} + C_{tax} = C_{pr} + C_{aid} \qquad (14)$$

The money inflow is income from selling a product or service C_{pr} and also eventually aid or subsidy C_{aid} from the state. The money outflow consists of cost for use of physical resources, e.g. energy C_{in}, cost for economic and human resources, i.e. capital $C_{capital}$ and labor C_{labor} and eventually an exergy tax C_{tax}. It should be noticed that we assume no profit, i.e. the system is acting in a free market economy with perfect competition where the equilibrium state is reached. By the exergy tax a company has to pay for using non-renewable resources and emitting exergy as waste to the environment. The income from these taxes could be used to support research and other activities to reduce exergy losses, i.e. reduce the impact to the environment, see Fig. 10. Thus, stimulate the development of sustainable engineering.

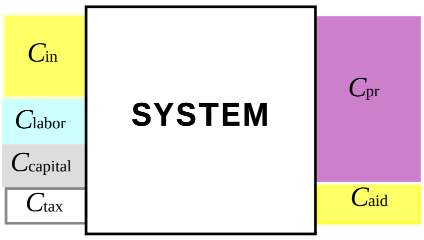

Figure 9 Monetary flow balance in the system. The money flow from right to left.

Assume a number of production systems of goods and services distributed on the market, either for direct consumption or for further production. In Fig. 10 we have production systems: 1, 2, etc. and a final consumer: 0. The flows are divided into two categories: (1) solid arrows: physical value and (2) outlined arrows: economical value.

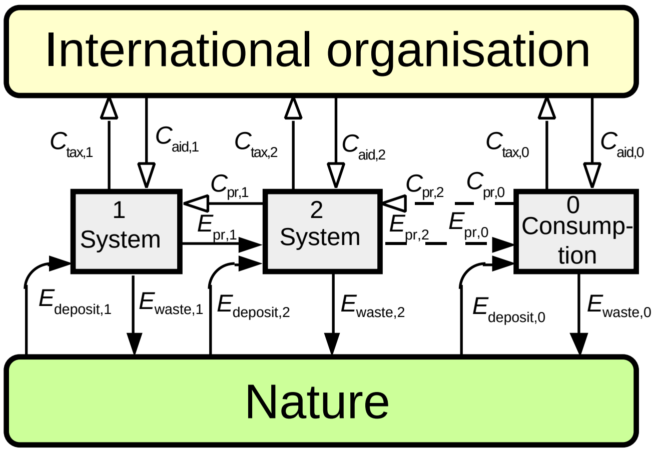

Figure 10 An international organization to tax resource depletion. (Note: Physical resources from natural flows and funds have been excluded since they are not taxed.)

Let us first consider the first production process. The company "produces" a physical value $E_{pr,1}$ and an exergy waste to the environment $E_{waste,1}$, as it consumes deposits $E_{deposit,1}$. (Since other flows are omitted, we can not apply, nor is there a need for mass or energy balances of the process.) At the same time, the economical values $C_{tax,1}$ and $C_{aid,1}$ are exchanged with the international tax-organization. The difference of these values, i.e. $C_{tax,1} - C_{aid,1}$ has to be added to the original cost of the product to get the final cost of the product, $C_{pr,1}$. The tax $C_{tax,1}$, is a function of the exergies, $E_{waste,1}$ and $E_{deposit,1}$, and toxicity. Thus, the companies are taxed in relation to the exergy consumption of deposits and the exergy waste and effect to the environment.

To use exergy as base for the tax has many advantages. (1) The exergy can be calculated from given physical data for the flow and the environment, which could be decided by international agreements. (2) The exergy is related to the utility of the extracted deposit, and to its physical (environmental) value, i.e., the physical "cost" to produce the resource from the ambient. (3) 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. (4) Exergy is always a positive value when we have a distinction from the natural (reference) environment, see Eq. 2.

The lack of recycling of physical resources in the society creates resource depletion and environmental destruction. By an exergy tax this could be changed. This tax should be governed by an international organization, e.g., the United Nations, since the effects usually are global.

Microeconomics and Exergetics

A system could be regarded as a part of two different environments — the physical and the economic environment. The physical environment is described by pressure P_0, temperature T_0, and a set of chemical potentials $\mu_{i,0}$ of the appropriate substances i, and the economic environment by a set of reference prices of goods and interest rates. These two environments are connected by cost relations, i.e. costs as a function of physical quantities, see Fig. 11.

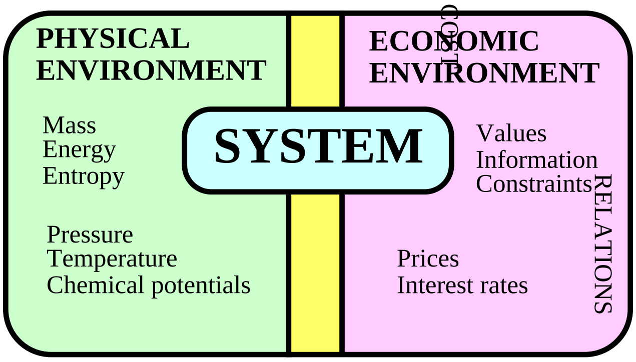

Figure 11 The system in two environments.

With the system embedded in the physical environment, for each component there are the mass and energy balances needed to define the performance of the system, which describe the physical behavior of the system, as we discussed above.

Let us define the best system as the system with lowest life cycle cost (LCC), i.e. the sum of the capital investment costs, operation and maintenance costs, and so on, as indicated in Eq. 15, for a given product during its life time. Thus, the objective function is

$$\Phi_0 = \mathrm{LCC} = \sum\left(C_{\mathrm{in}} + C_{\mathrm{labor}} + C_{\mathrm{capital}} + C_{\mathrm{tax}} - C_{\mathrm{aid}}\right) \qquad (15)$$

which should be optimized, i.e. minimized for a given product. By reducing the cost per product the company can offer the product at a lower price than the present market price, thus be come more competitive.

If we know the cost relations, we are able to link the physical and economic environments. The cost equation can sometimes be simplified as a scale effect times a penalty of intensity. Then we can find the system of lowest cost which is physically feasible. Usually the maintenance and capital cost of the equipment is not a linear function, so in many cases these costs have more complex forms. 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

Thermoeconomic accounting method is based on the pioneer work of Gaggioli (1961) and his co-workers as well as Tribus and his co-workers (Evans and Tribus, 1962, 1965).

Since exergy measures the physical value, and costs should only be assigning to commodities of value, exergy is a rational basis for assigning costs to the interactions that a physical system experiences with its surrounding and to the sources of inefficiencies within it. The exergy input is shared between output and destruction, or product and losses.

Thermoeconomic accounting simply means determining the exergy flows and assigning economic values to the exergy flows. When there are various in- and outflows, 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.

Monetary balances of the form (Eq. 14) are formulated for the total system, and for each component of the system, being investigated. Exergy accounting gives a good picture of the monetary flows inside the total system and is a way to analyze and evaluate very complex installations.

Thermoeconomic accounting does not include consideration of the 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 the thermoeconomic accounting method the exergy losses are figures not functions. However, this simple type of analysis sometimes gives ideas for, otherwise, not obvious improvements.

Thermoeconomic optimization

Thermoeconomic optimization considers how the capital investments in one part of the system affect other parts of the system, thus optimizing the objective function, Φ_0, i.e. the total cost of the system.

The objective function Φ_0 should preferably be defined as a function of state parameters $\{x_j\}$[7], decision variables $\{y_k\}$, and decision parameters $\{z_l\}$, i.e.

$$\Phi_0 = \Phi_0(\{x_j\},\{y_k\},\{z_l\}) \qquad (16)$$

where j=1, 2,…, n, k=1, 2,…, m, and l=1, 2,…, r.

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

$$\Phi_j(\{x_i\},\{y_k\},\{z_l\}) \qquad j = 1, 2,\ldots, n. \qquad (17)$$

Thus, the optimization is formulated as follows:

$$\text{Minimize } \Phi_0 = \Phi_0(\{x_i\},\{y_k\},\{z_l\}) \qquad (18)$$

$$\text{Subject to } \Phi_j(\{x_i\},\{y_k\},\{z_l\}) \qquad j = 1, 2,\ldots, n. \qquad (19)$$

where 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:

$$\theta_k = \frac{\Delta\Phi_0}{\Delta y_k} \qquad k = 1, 2,\ldots, m \qquad (20)$$

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 define the marginal costs of exergies to find where exergy improvements are best paid off in the system.

[7] $\{x_j\}$ is abbreviation for $x_1, x_2, \ldots x_j \ldots x_n$

Optimization versus improvement

Finally, we only want to draw some attention to the difference between optimization and improvement. 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 Eq. 15. It is also important not to be mislead 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.

CONCLUSIONS

Exergy is a useful concept since it is a link between the physical and engineering world and the surrounding environment. Exergy also expresses the true efficiency of engineering systems, which makes it a useful concept to find improvements. Therefor, we strongly recommend that exergy is used in the design of engineering systems.

Methodologies based on exergetics and economics are developing, and will soon gain global acceptance as useful tools for optimizing the design, operation and maintenance of energy systems. By adopting the methods of exergy flow diagrams and LCEA engineering for a sustainable society could be further realized.

ACKNOWLEDGMENT

We wish to express our gratitude for Dr. Darwish M. K. Al Gobaisi, International Center for Water and Energy Systems in Abu Dhabi, U. A. E. who made this work possible.

REFERENCES

Bejan, A., Tsatsaronis, G. and Moran, M., 1996, *Thermal design and optimization*, Wiley.

Boulding, K. E., 1966, “The economics of the coming spaceship earth,” in Environment quality in a growing economy, ed. H. Jarrett, Baltimore: Johns Hopkins Press.

Brodyansky, V. M., Sorin, M. V. and Legoff, P., 1994, *The efficiency of industrial processes: exergy analysis and optimization*, Elsevier.

Chapman P. F. and F. Roberts, 1983, *Metal Resources and Energy*, Butterworths.

Evans, R. B. and Tribus, M., 1962, “A contribution to the theory of thermoeconomics,” UCLA Department of Energy: Report No. 62-63, Los Angeles, CA.

Evans, R. B. and Tribus, M., 1965, “Thermoeconomics of Saline water conversion,” I&EC process design and development, **4**, pp. 195-206.

Gaggioli, R, A., 1961, “Thermodynamics and the non-equilibrium system,” Ph. D. thesis, Univ of Wisconsin-Madison.

Goodstein, D., 1994, *Nature*, Vol. 368, 14 April, p. 598.

Grassman, P., 1950, Chemical Energy Technik, **4**, pp. 77-80.

Gouy, G., 1889, “About available energy”(in French), *Journal Physique II*, **8**, pp. 501-518.

IFIAS (International Federation of Institutes of Advanced Study), 1975, Workshop reports, “Energy Analysis”, report no. 6, 1974 and “Energy Analysis and Economics”, report no. 9, 1975. For a short summary see: L. Kristoferson and S. Nilsson, *Ambio*, vol. 5, p. 27, 1976.

Kostenko, G., 1983, Promishlenaya Teplotechnika, **4**, pp. 70-73.

Same, D. A., 1995, “Second law insight analysis compared with pinch analysis as a design method,” *Second law analysis of energy systems: Toward the 21-st century*, Rome, July 5-7, Esagrafica-Roma, pp. 373-406.

Spreng, D. T., 1988, *Net-Energy Analysis and the Energy Requirements of Energy Systems*, Praeger.

Stodola, A., 1898, “The cyclic processes of the gas engine” (in German), *Z. VDI*, **32**, no. 38, pp. 1086-1091.

Szargut, J., Morris, D. R., 1987, *Cumulative Exergy Consumption and Cumulative Degree of Perfection of Chemical Processes*, Int. J. Energy Res. Vol. 11, pp. 245-261.

Tribus, M, and El-Sayed, Y., 1982, “Introduction to Thermoeconomics”, Compendium, M.I.T.

Wall, G., 1977, “Exergy — a useful concept within resource accounting”, Institute of Theoretical Physics, Göteborg. Report no. 77-42.

Wall,, G., 1993, “Exergy, Ecology and Democracy — Concepts of a Vital Society”, presented at “ENSEC’93 International Conferens on Energy Systems and Ecology”, 5-9 July, 1993, Cracow, Poland, publ. in Szargut, J., et al., Eds., pp. 111-121.

Wall, G., 1995, “Exergy and Morals”, *position paper at* “Second Law Analysis of Energy Systems: Towards the 21st Century,” July 5-7, 1995, Rome, Italy, publ. E. Sciubba & M. J. Moran, Eds. Roma, pp. 21-29.

Yantovskii, E. I., 1994, *Energy and Exergy Currents*, Nova.