On Exergetics, Economics and Desalination

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Keywords: Exergy, Exergy Analysis, Exergetics, Thermoeconomics, Life Cycle Analysis, Desalination.

CONTENTS

1 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, e.g., desalination processes. Exergetics and microeconomics forms the basis of thermoeconomics, which is also named exergoeconomics and exergonomics. 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." "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."

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. In addition, a designer should also have a basic knowledge in ecology and sociology, as well as ethics and morals.

This article introduces the concept of exergy, different ways to define exergy efficiency, and distinguishes between exergy destruction, i.e., irreversibility and exergy loss or 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 is presented, as well as the application of exergetics in micro- and macroeconomics. Exergy is a useful concept in the analysis of systems involving both thermal and mechanical energies, as most desalination processes, e.g., in Multistage Flashing (MSF) and Multiple Effect Boiling (MEB). Reverse Osmosis (RO) uses only electrical or mechanical exergy.

Fresh water is a scarce resource in most parts of the world. Thus, it is very important to develop efficient and sustainable methods of desalination. Physically, desalination is a matter of separation, i.e., to separate salt from water by different means. Imagine that we have 100 molecules, i.e., particles, of seawater of which 2 are salt and the rest pure water molecules. If they are completely mixed, than the probability that we pick a water molecule is directly proportional to its fraction in the mixture, i.e., 0.98 or 98%. However, if we have picked one water molecule, the probability to pick another one is slightly reduced, or 97.98%. Thus, the saltier the water becomes, the harder it is to desalinate.

2 EXERGETICS

In 1824 the Second Law of thermodynamics was first expressed by N. L. Sadi Carnot. It resulted from his attempt to find a general expression for the maximum amount of work that can be done by an engine for converting heat into mechanical work. The first analytical expression of the second law did not occur until 1865 when Clausius introduced entropy. The notion of available work, including the diffusion term, was first introduced by Willard Gibbs in 1873.

Exergy is a thermodynamic potential, it is a general measure of "difference." It has been interpreted as "available" energy, "the capacity to do work", and the "transformable or convertible component of energy". Evans, Tribus and coworkers introduced the term essergy (for "essence of energy"), and linked classical thermodynamics with information theory. In 1953 the term *exergy* was suggested by Z. Rant, it denotes "technical working capacity". Besides exergy and essergy, the variable has been called availability, available work, distinguishability, contrast, potential entropy and physical information. At an international conference in Rome, 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. Recently, the concept of exergy is widely used.

2.1 Exergy on the earth

Energy and matter cannot be created or destroyed. We can not understand what energy actually is, since everything we can observe is energy in different forms. Thus, one way to define energy is that it is everything. Another way is to define energy as motion or ability to produce motion. Energy and matter appears in many forms and different qualities and the quality can increase locally or be destroyed. However, the total quality of a closed system must always decrease. This is best explained by the concept of exergy. When we use the word energy in everyday life we should, if accurate, use the word exergy instead. Exergy can be defined as work or ability to produce work. Work is ordered motion, in distinction to energy. In short, we can mostly state that nothing disappears and everything disperse.

Let us illustrate the meaning of *exergy* by some very simple examples:

1. A system in complete equilibrium with its environment does not have any exergy. There is no difference in temperature, pressure, or concentration etc. that can drive any processes. Thus, a waste flow, of any kind, with no exergy does, by definition, not influence the environment.

2. The more exergy a system carries, the more it deviates from the environment. Hot water has a higher content of exergy during the winter than it has in a hot summer day. A block of ice carries hardly any exergy in winter while it does in summer. This fact was the basis of a very prosperous trade of ice in the nineteenth century, when ice was regularly shipped from North America to West Indies, South Africa, and finally to Europe.

3. When a physical resource, i.e. energy, matter or information, loses its value, this means that exergy is destroyed. The exergy is the part of the resource which is useful in the society and therefore has an economic value and is worth taking care of.

4. Exergy is consumed in the constant flows of energy and matter that go on within and in-between all systems on the earth. The driving source for the whole system is exergy that is pumped into it from outside. This process is illustrated in Figure 1. Exergy from the contrast between the sun and space drives flows of energy and matter on the surface of the earth. There is a balance between the inflow and the outflow of energy. The average temperature on the earth's surface is determined by, among other things, the amount of energy that radiates towards the earth. Matter is transported via countless cycles through systems on earth. The circulation periods for these cycles of matter can vary from splits of seconds to billions of years. Examples of parts of such cycles can be nerve impulses in a cell and mining in a human society.

Energy-rich 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 1, this part of the process was omitted and the inflowing sunlight is thus the net flow of sunlight reaching the earth. The energy of this flow is converted on earth, and thereafter it leaves the earth as heat radiation. The exergy of the sunlight is, however, consumed on earth. The incoming solar radiation is relatively short-wave radiation and therefore has a high quality. The outgoing heat radiation is, however, long-wave and consequently of low quality. The whole of the earth can thus be seen as an immense machine picking up exergy from the sun. 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 motive force is always the difference in quality between visible sunlight and outgoing invisible heat radiation.

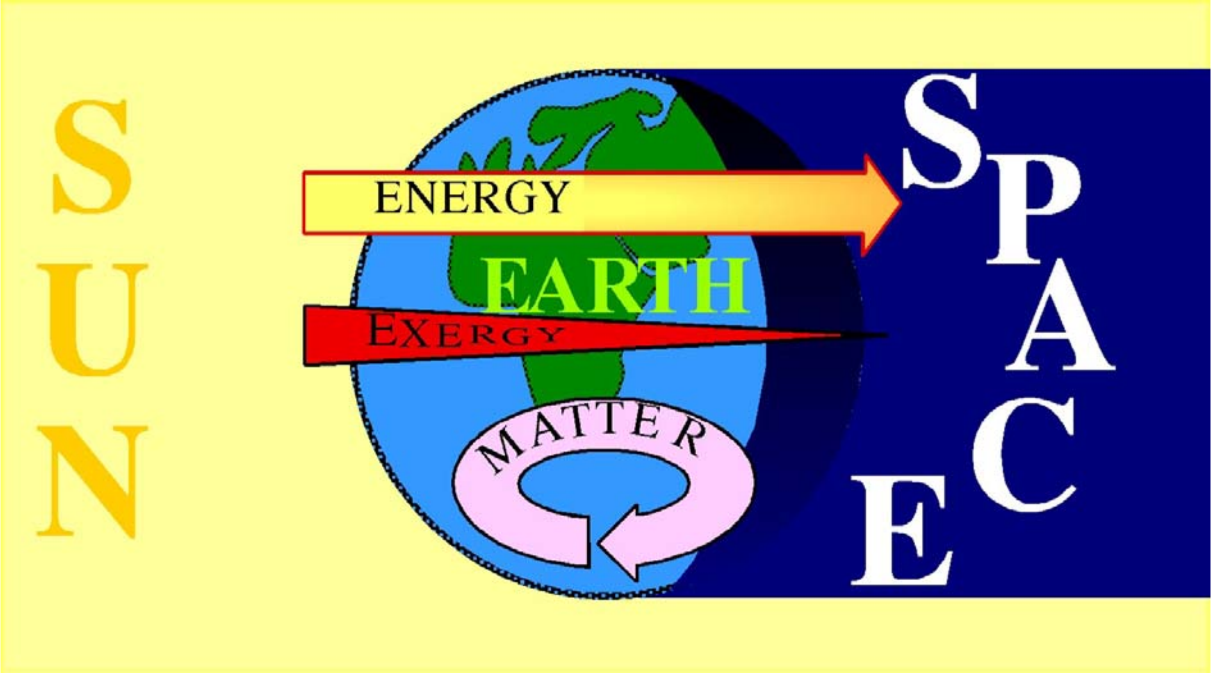

Figure 1 Flows of energy and matter on earth are driven by exergy, i.e. the contrast between the sun and space

5. Almost all energy, converted in the thin layer on the earth's surface, where life can be found, derives from the sun, see Figure 2. A small fraction origins from the earth itself as geothermal effects and the moon as tidal effects. About 13000 times the energy used in the human society reaches the earth as solar energy. A lot of it, or about one forth, is reflected, mainly the harmful ultraviolet light by the ozone layer. This light gives the beautiful shimmering blue photos of the earth. Half of the energy is converted into heat and hereby powering the climatic system. Merely the water circulation in the hydrosphere takes about 3000 times the energy which is converted in the sociosphere by man. The total amount of water being evaporated adds up to about 450,000 km^3 of fresh water per year, i.e. a cube where each side is about 77,000 m. The energy absorbed on the earth is converted and finally leaves the earth as heat radiation with no exergy relative to the earth. In Figure 3 the situation is shown in terms of exergy. Sunlight, which is rich in exergy, reaches the earth. Most of this is consumed on the earth, only the reflected light is emitted back into space. The net exergy absorbed by the earth is consequently gradually destroyed, but during this destruction it manages to drive the climate and the life on earth. We see this as ending exergy flows. The exergy is consumed and the systems on earth are maintained and developed. The living nature and the society will be further presented below.

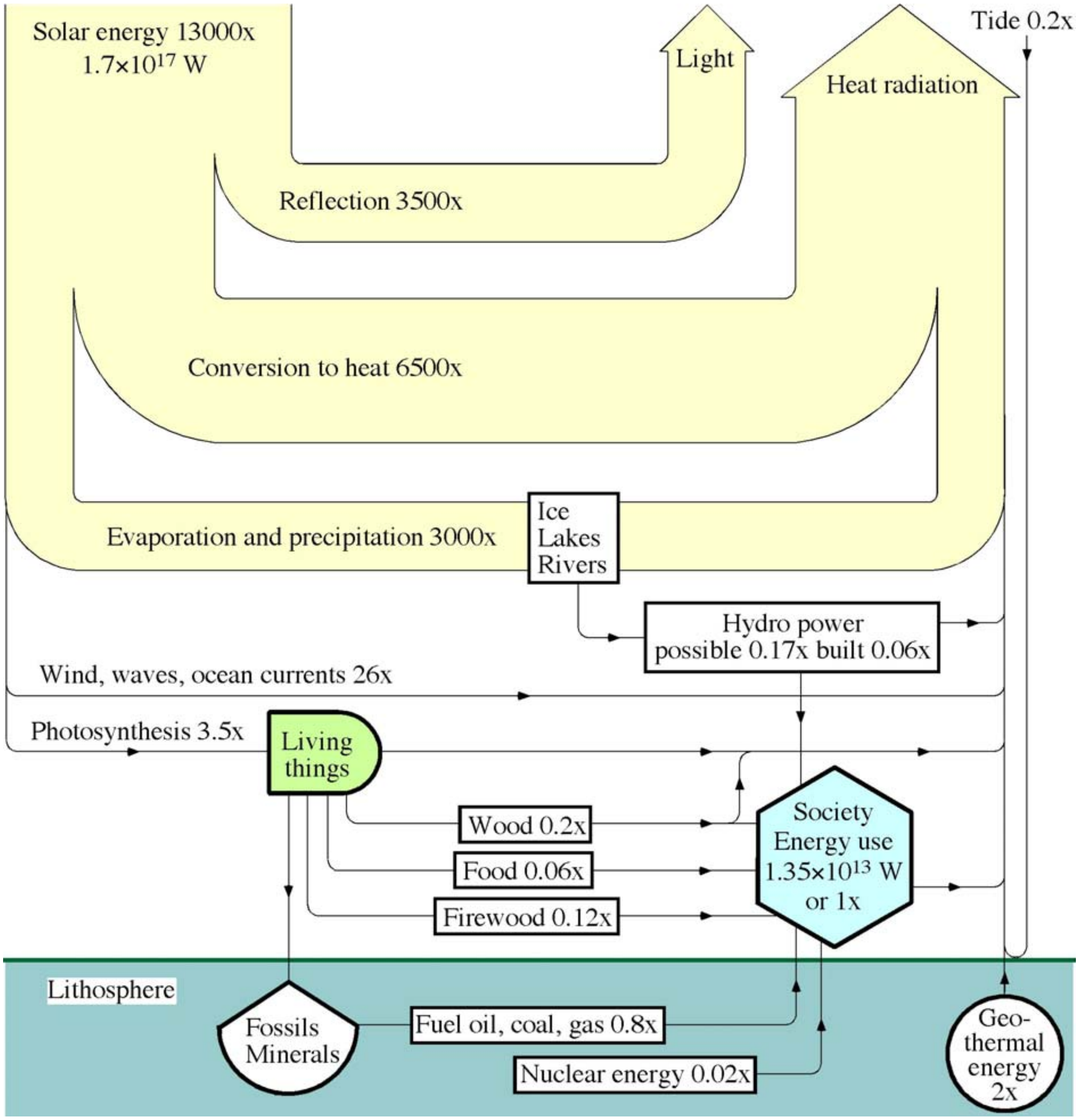

Figure 2 The energy balance on the earth

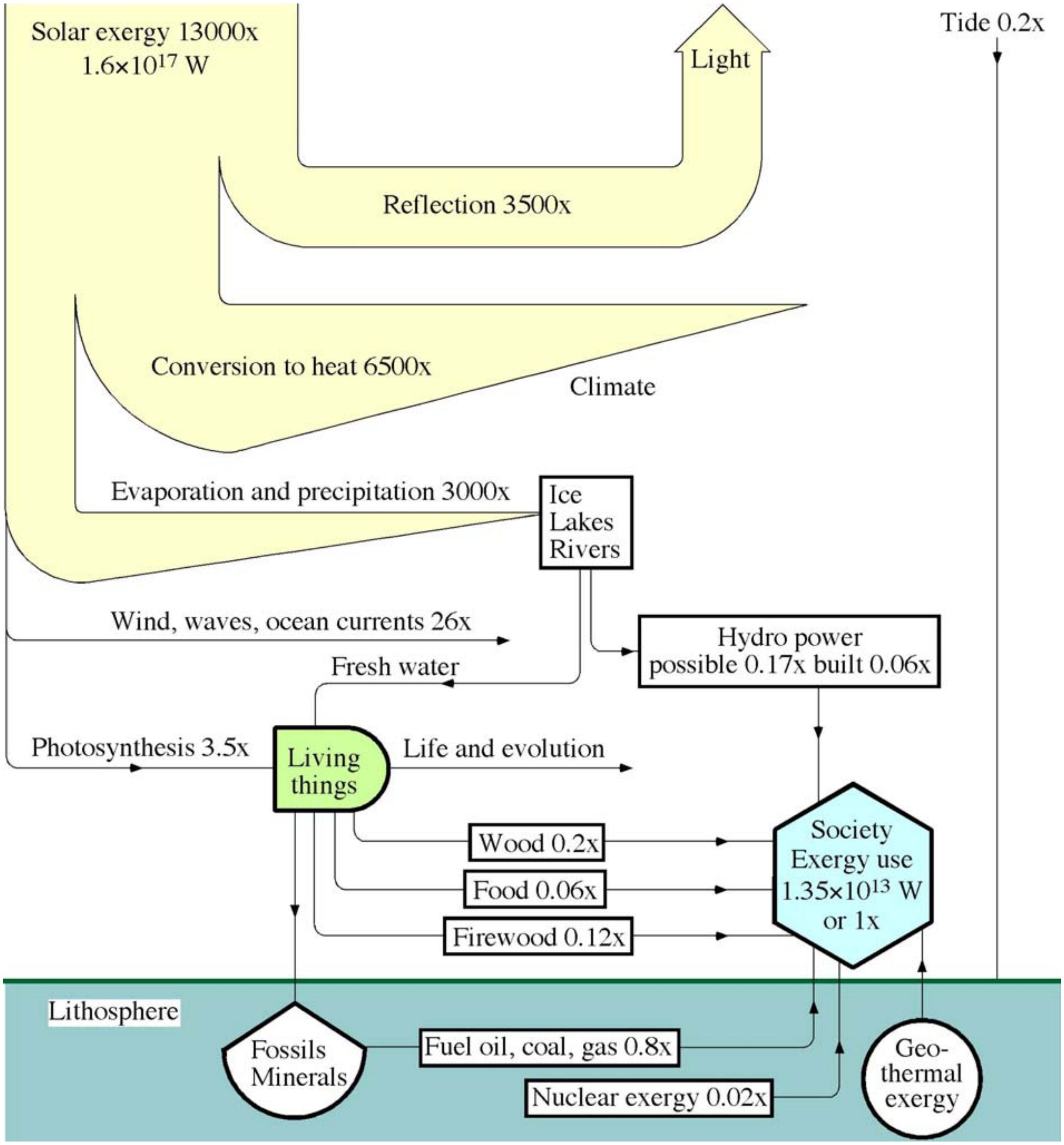

Figure 3 The exergy flow on the earth

6. The green plants are the main suppliers of power to all living things on the earth, i.e. the source of life, see Figure 4. Complex structures, rich in exergy and capable of reproduction, are formed by photosynthesis in the biosphere. The green plants pick up exergy from sunlight by photosynthesis, and convert it into chemical exergy in materials, i.e. biomass, which then pass through different food-chains. At every link, exergy is consumed. The last link represents micro-organisms, which decompose the materials back into its original substances. There exists no waste, i.e. all exergy is being taken care of and efficiently used by the living nature. The exergy that cannot be utilized by these organisms instead forms 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. Stocks in the form of living and dead organic matter on 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.

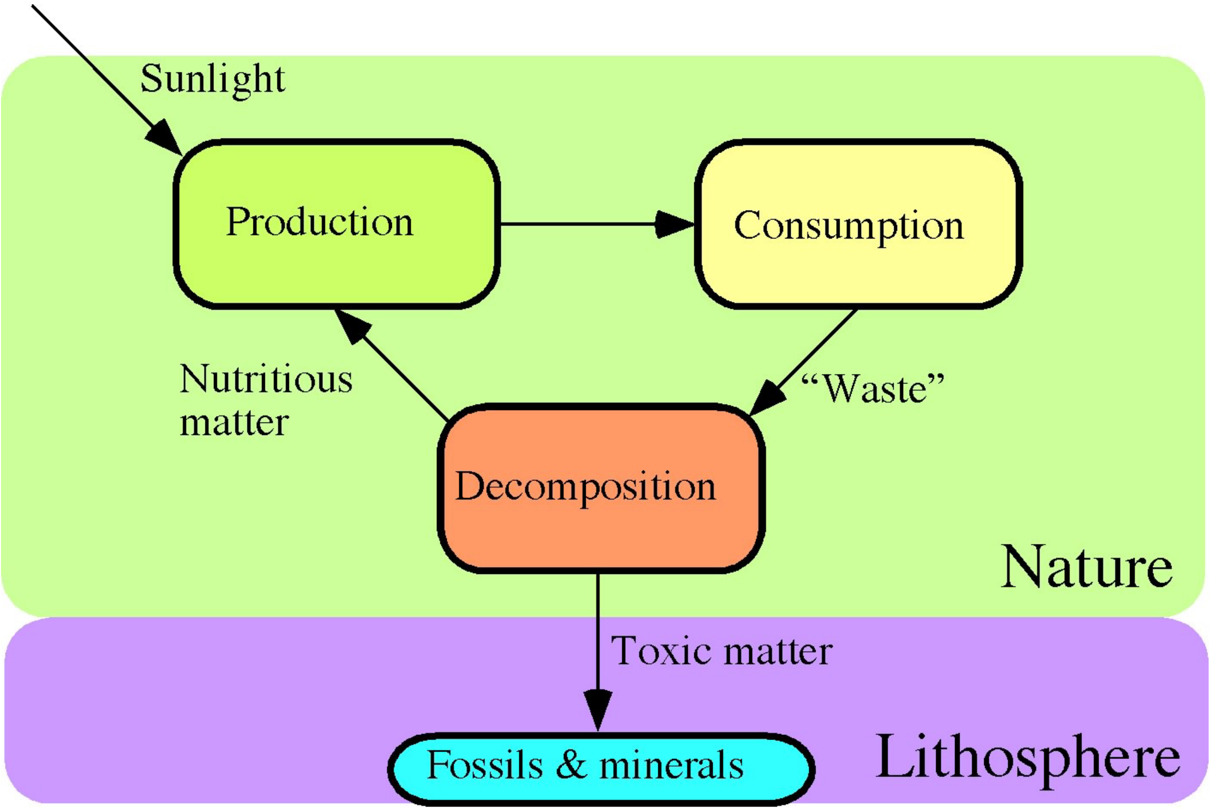

Figure 4 The natural evolution is forced by sunlight and is "self creating"

7. A concentrated deposit of mineral "contrasts" with the environment and this contrast increases with the concentration of the mineral. The mineral is thus a carrier of exergy. When the mineral is mined, the exergy content of the mineral is kept constant, and if it is enriched the exergy content increases. A poor deposit of mineral contains less exergy and can accordingly be utilized only through a larger input of external exergy. Today this substitution of exergy often comes from exergy forms such as coal and oil. When a concentrated mineral is dispersed, the exergy is lost as waste. From the environmental point of view this exergy waste may be harmful to the environment.

8. The exergy of a substance depends on the environment, which may differ from place to place. By conventions one could define a "standard environment" with a given chemical composition at a certain temperature and pressure. A standard environment for global use could be a standard atmosphere, a standard sea and a standard bed-rock. One principal problem is, however, that these systems are not in equilibrium with each other. Sometimes one should, in addition to this, use local environmental standards, which also may depend on the season. Commonly used reference states have been stated by Szargut.

In Figure 5, we see how the exergy flow through human society is maintained, cf. Figure 4. The greater part of the exergy requirements are seen to from the terrestrial exergy stocks. Man only uses a very small part of the exergy flow from the sun, e.g. within agriculture and forestry. In society there is thus, on the whole, a continuous exergy loss. Some exergy flows, such as flows of ores and desalinated water, increase their exergy when passing through society. However, other flows decrease their exergy all the more.

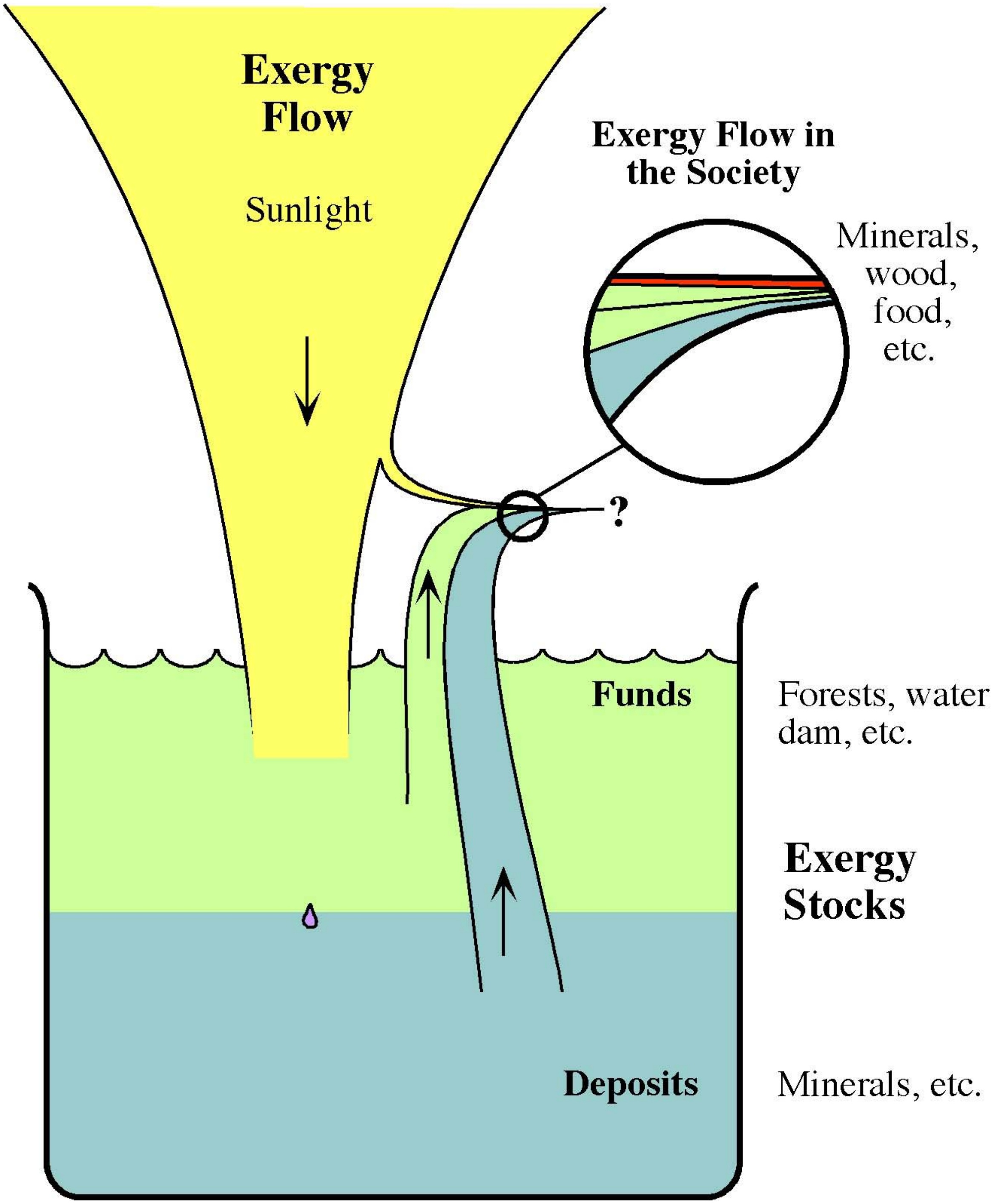

Figure 5 The exergy flow from the sun, and the exergy stocks on earth create the resource base for human societies on earth

2.2 Exergy in thermodynamics

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, it presents quality, then the environment must be specified, i.e. a reference environment. Usually the reference temperature (T_o) is 298.15K and the reference pressure (P_o) 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 systems. Pressure and chemical conditions also vary around the globe. A huge thermodynamic potential is also built up by the deposits of fossil fuels and the existence of oxygen in the atmosphere.

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:

$$\delta Q = dU + \delta W \tag{1}$$

defines energy as a conserved quantity and work, as a product between an intensive and an extensive quantity:

$$\delta W = PdV \tag{2}$$

where V is the volume.

2nd law:

$$dS \geq 0,\ dS_{reversible} = 0 \tag{3}$$

defines the concept of entropy through heat and temperature:

$$\delta Q = TdS \tag{4}$$

analogous to relation (2).

3rd law defines the zero level for entropy, i.e., normalizes the entropy scale.

Thermodynamics only treats reversible processes, i.e., processes with no direction in time, for systems in equilibrium states. Thus, a more proper name is thermostatics. Even though, thermodynamics is one of the most useful parts of physics in engineering.

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 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.” In Table 1, we have summarized the main differences between energy and exergy.

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.
$\Delta Q = \Delta U + \Delta W$ (5) 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.,	$E = T_o(S_{eq}^{tot} - S^{tot})$ (6)[2] where: E is exergy, T_o is the temperature of the environment, S_{eq}^{tot} is the entropy of the total system, i.e., the system and the environment at equilibrium state, S^{tot} is the entropy of the total system at a given state
$E = mc^2$ (7)[3] Energy and matter m is “the same thing.” Everything is energy.	$E = k \ln 2 T_0 I$ (8)[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 in 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 and 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 article, m is mass, c is the speed of light in vacuum, which is equal to about 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, where I is information, or information capacity (bit) and k is the Boltzmann constant, 1.38054×10^{-23} J/(molecule) K. The gas constant R is Avogadros number, 6.022×10^{23} times k, i.e., 8.314 J/mol K.

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

2.3 Exergy losses

For real processes the exergy input always exceeds the exergy output, this unbalance is due to irreversibilities, which we also 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, i.e., resource depletion, 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, thus, no direct environmental effects. However, a large exergy destruction may imply a large use of exergy input that may cause environmental damage.

The exergy destruction ΔE is related to the entropy production by

$$\Delta E = T_o \Delta S^{tot} = E_{in}^{tot} - E_{out}^{tot} = \sum_i \Delta E_i \qquad (9)$$

where ΔS^{tot} is the total entropy increase, E_{in}^{tot} is the total exergy input, E_{out}^{tot} is the total exergy output, 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 in one part, 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.

2.4 Exergy Efficiency and Exergy Flow Diagrams

Exergy efficiency, which is also called second law efficiency, effectiveness, or rational efficiency, 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, due to, e.g., time constraints.

A simple definition of efficiency expresses all exergy input as used exergy, and all exergy output as utilized exergy. So the exergy efficiency $\eta_{ex,1}$ becomes

$$\eta_{ex,1} = \frac{E_{out}}{E_{in}} = 1 - \frac{\Delta E}{E_{in}} \qquad (10)$$

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.,

$$E_{out} = E_{pr} + E_{waste} \qquad (11)$$

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

$$\eta_{ex,2} = \frac{E_{out} - E_{waste}}{E_{in}} = \frac{E_{pr}}{E_{in}} = \eta_{ex,1} - \frac{E_{waste}}{E_{in}} \tag{12}$$

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}, see Figure 6.

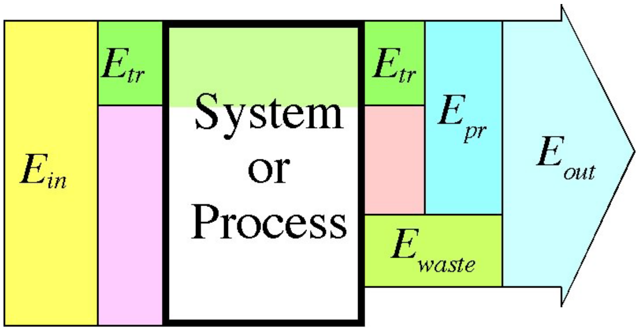

Figure 6 The input and output of exergies for a system

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

$$\eta_{ex,3} = \frac{E_{out} - E_{waste} - E_{tr}}{E_{in} - E_{tr}} = \frac{E_{pr} - E_{tr}}{E_{in} - E_{tr}} \tag{13}$$

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

$$\eta_{ex} = \eta_{ex,2} = \frac{E_{out} - E_{waste}}{E_{in}} = \frac{E_{pr}}{E_{in}} \tag{14}$$

Let us compare these latter definitions by applying them to a system with two different processes A and B, see Figure 7. 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.

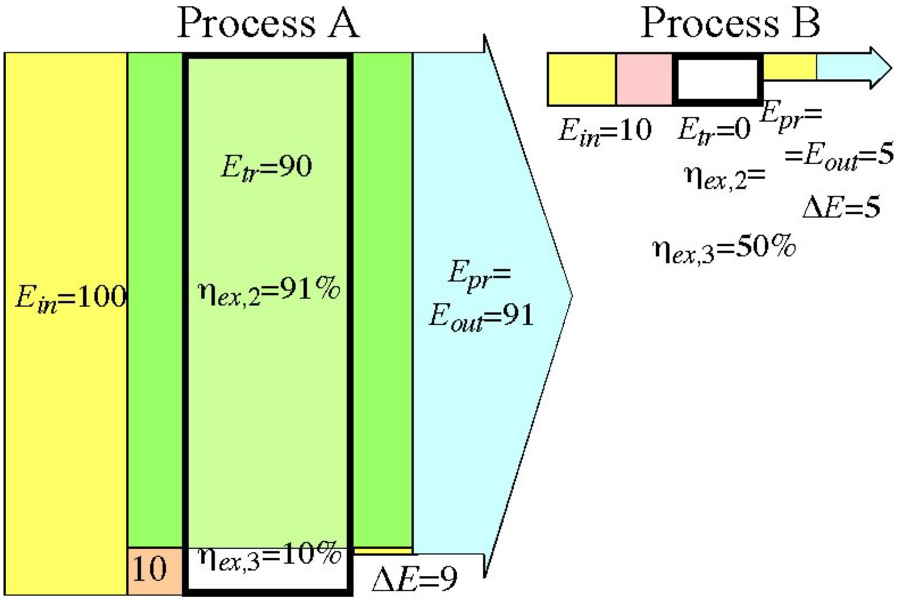

Figure 7 Comparing efficiencies with exergy flows of two processes A and B

From this comparison we see that a better insight is offered by using exergy flow diagrams, which are also called Sankey-Grassman diagrams, or just Sankey diagrams. 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
- which part is transiting exergy
- how much exergy is destroyed in each processes.

"Again, ambiguity is eliminated if a Sankey diagram is used instead of a ratio to summarize an energy account."

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

2.5 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. It has been suggested to use exergy instead and call the method **exergy analysis**.

There are basically three different methods used to perform an exergy analysis, these methods are process, statistical and input-output analysis. 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: firstly, it can achieve a more detail analysis, and secondly, 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 Figure 8, focuses on a particular process or sequence 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.

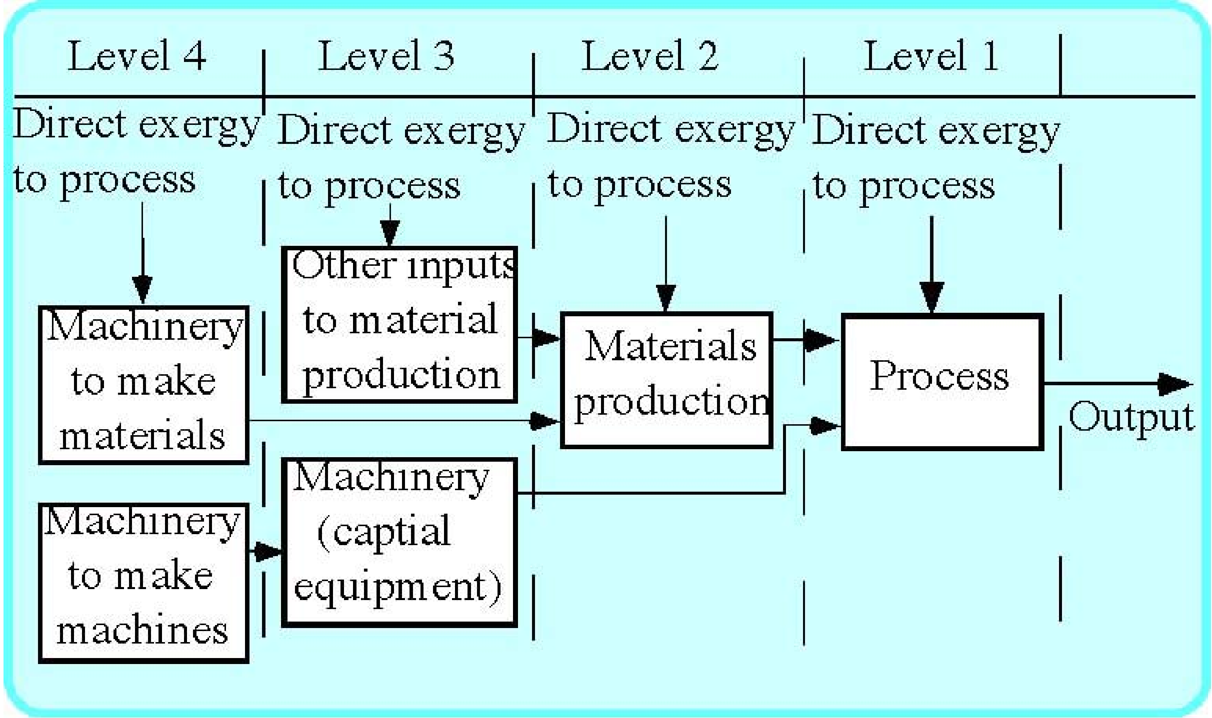

Figure 8 The levels of an exergy process analysis

Also, the more clarifying name **net-energy analysis** has been used for this kind of analysis. This method is described in terms of exergy in Figure 9. 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.

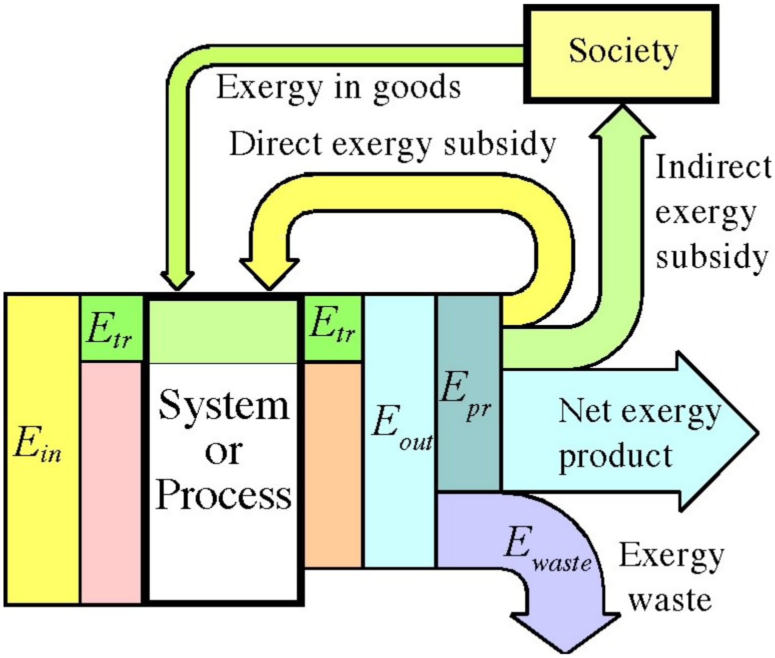

Figure 9 Net-exergy analysis

Szargut and Morris 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, i.e., exergy process analyses as above.

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. LCEA is a superior tool in this regard.

Resources must also be classified, see Figure 10, in order to relate an analysis to degree of sustainability. 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 are renewable and deposits are non-renewable resources. Funds that are used in a sustainable way, i.e. the tap is less than the growth, are renewable, but if they are used in a non sustainable way they can not be regarded as renewable, e.g., the clear-cutting forest. We must also consider the total exergy use over time.

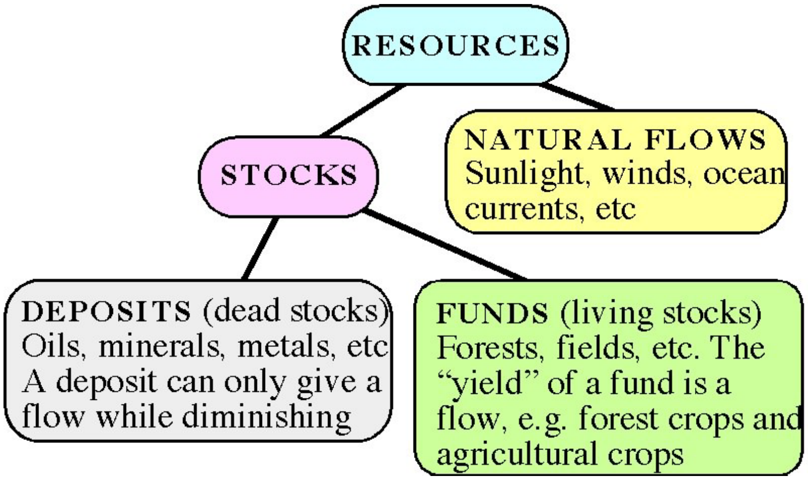

Figure 10 Classification of resources

The exergy flow through a system, usually consists of three separate stages over time, see Figure 11. At first, we have the construction stage where exergy is used to build a plant and put it into operation. During this stage, $0 \leq t \leq t_{start}$, 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 a power plant is put into operation, it starts to deliver exergy power $\dot{E}_{pr}$, by converting the direct exergy power input $\dot{E}_{in}$. 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.

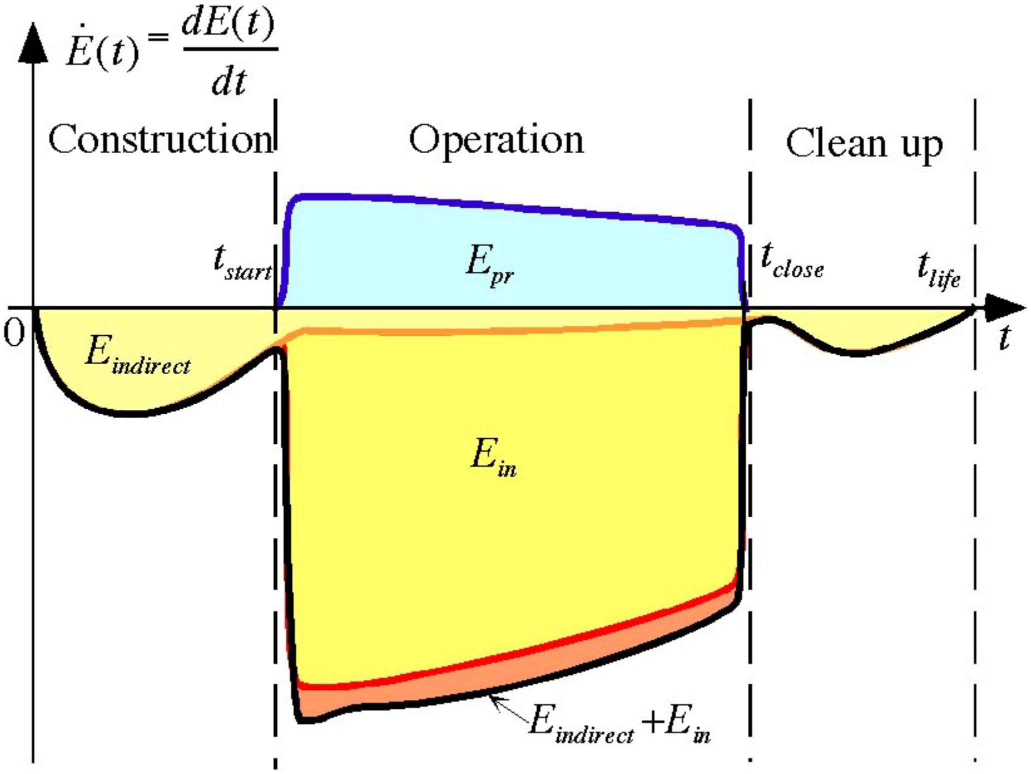

Figure 11 Exergy use during a systems life cycle

In the first case, we disregard, from a sustainability point of view, the direct exergy input, since this originates from natural flows, i.e., renewable resources. Then, at time $t = t_{pay\ back}$ the delivered exergy has covered up for the indirect exergy input, see Figure 7, i.e.

$$\int_{t_{start}}^{t_{pay\ back}} \dot{E}_{pr}(t)dt = \int_{o}^{t_{life}} \dot{E}_{indirect}(t)dt = E_{indirect} \tag{15}$$

Thereafter, there will be a net exergy output from the plant, 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 15. By considering the total life cycle of the plant the net delivered exergy becomes:

$$E_{net,\, pr} = E_{pr} - E_{indirect} = \int_{o}^{t_{life}} \dot{E}(t)dt \tag{16}$$

These areas representing exergies are indicated in Figure 7.

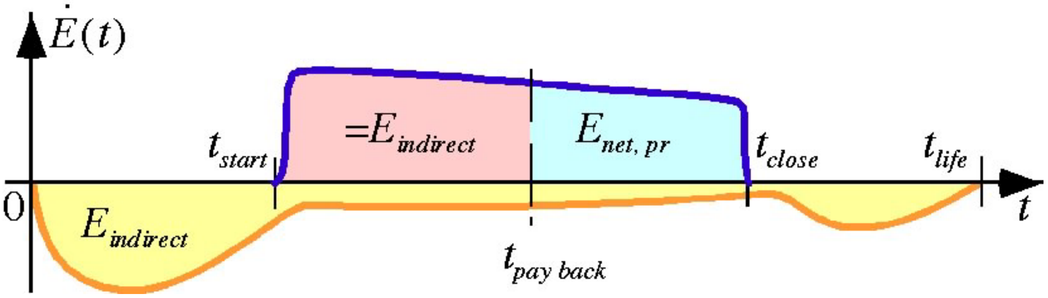

Figure 12 Exergy use during a systems life cycle

In the next case, we consider all direct exergy input, since we use a deposit or non-renewable resource which will be ruined from the use and perhaps also bring harmful effects to the environment. This is always the situation in the use of deposit resources like minerals and fossil, e.g., metals and fossil fuels. Figure 12 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

$$E_{pr} < E_{in} \tag{17}$$

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, that 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 must therefor be done in the design of such systems in order to avoid this kind of misuse.

Sustainable engineering, ecological design 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 as well as **sustainable desalination**.

3 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, 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 economists 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 characterizes these two views as the cowboy and spaceman economies:

> "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 LCEA and an exergy tax.

Macroeconomics is also acting as a political tool at the global level to maintain poverty in the world. Most international meetings on the subject reach the same conclusion: the starving world can only get food if the rich world gets even richer. Still, anyone can see that the problem is not lack of food, it is the distribution of it. Thus, a more correct description of the situation is greediness. Today greediness is also acting towards future generations on this planet, i.e., our children. Oren R. Lyons, Chief of the Onondaga Nation, an indigenous society of America, has addressed the problem accordingly: a society not governed by morals has no future. Therefore, morals is of essential importance, together with the concepts of exergy, ecology and democracy to create a sustainable or rather vital society.

3.1 Exergetics and Macroeconomics

The world faces a lack of non-renewable resources and an environmental destruction. In order to encourage the use of renewable resources and to improve the resource use, an exergy tax could be introduced. In Figure 13 we have divided the resource inflow into two parts, renewable and non-renewable resources. The outflows are divided into products and waste. The inflow of non renewable resources and the waste, should be taxed by the amount of exergy since this is related to the environmental impact. In addition to this, toxicity and other indirect environmental effects must also be considered. In the case of irreversible environmental damage, a tax is not suitable, instead restrictions must be considered.

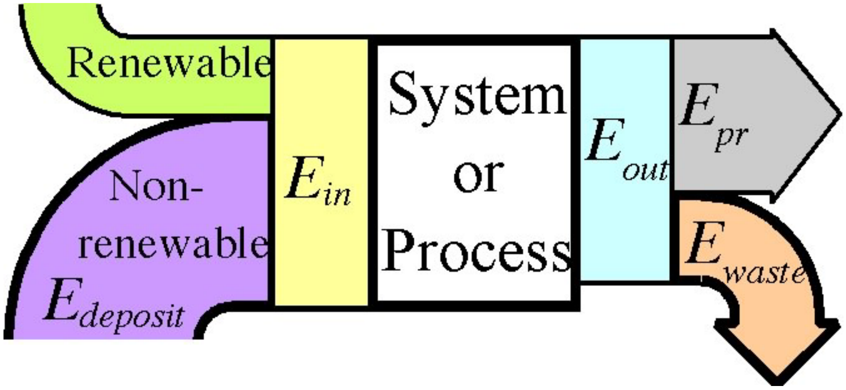

Figure 13 Exergy taxed in the system, outlined flows should be subject to tax

In economics systems are subject to a monetary balance, see relation 18 and Figure 14, where we have added an exergy tax C_{tax} and an aid C_{aid}.

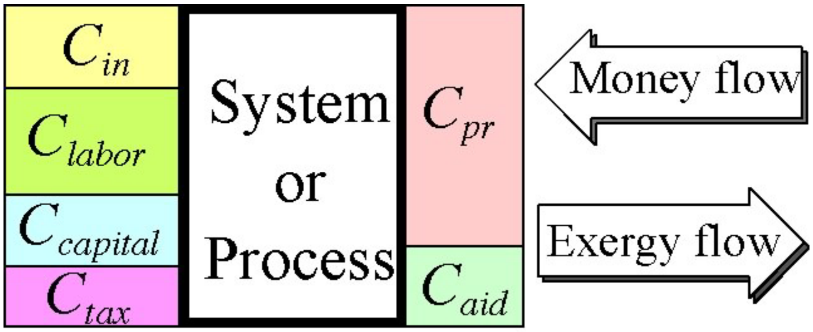

Figure 14 Monetary flow balance in the system

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}.

$$C_{in} + C_{labor} + C_{capital} + C_{tax} = C_{pr} + C_{aid} \tag{18}$$

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 Figure 15.

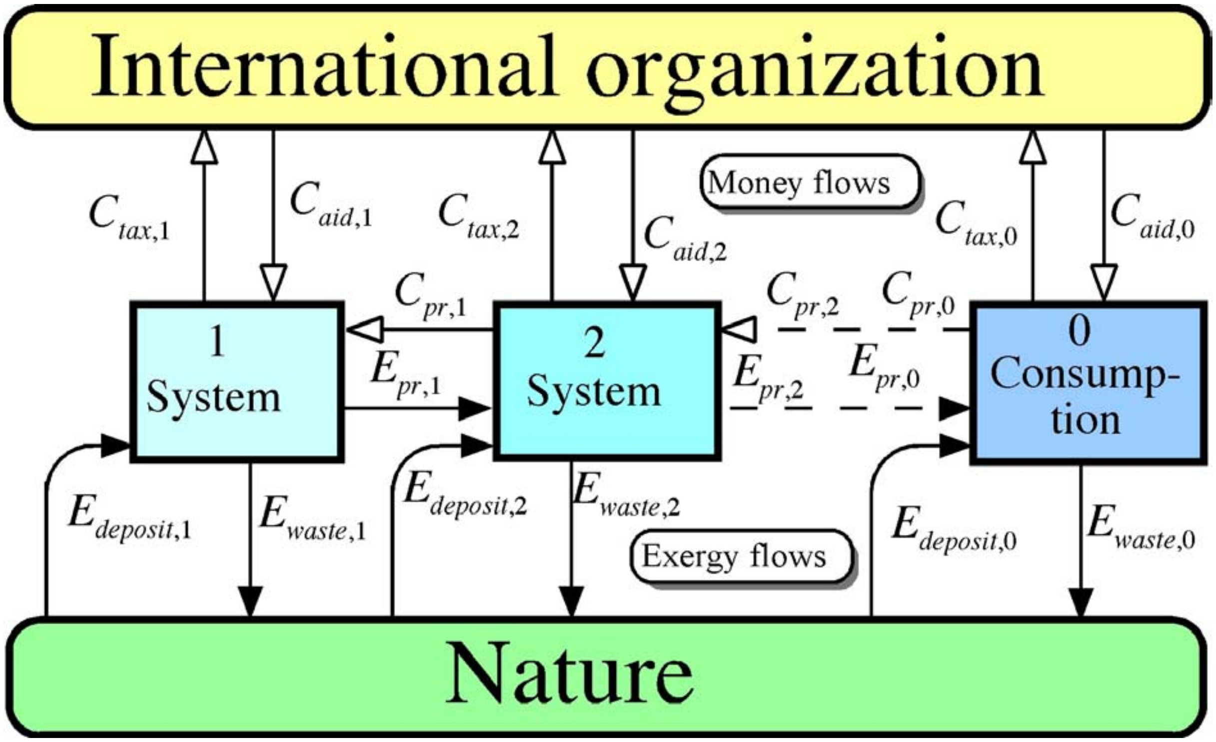

Figure 15 An international organization to tax resource depletion.

Assume a number of production systems of goods and services distributed on the market, either for direct consumption or for further production. In Figure 15 we have production systems: 1, 2, etc. and a final consumer: 0. The flows are divided into two categories: (the lower half) solid arrows: physical values or exergy flows and (the upper half) outlined arrows: economical values or money flows. Observe that physical resources from renewable resources 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 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.

- 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 (reference) environment, see relation 3.

- Exergy also offers an excellent internal efficiency concept to improve a system or process to meet these requirements in an optimal way.

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.

3.2 Exergetics and Microeconomics

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_o, temperature T_o, and a set of chemical potentials $\mu_{i,o}$ 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., cost as a function of physical quantities, see Figure 16.

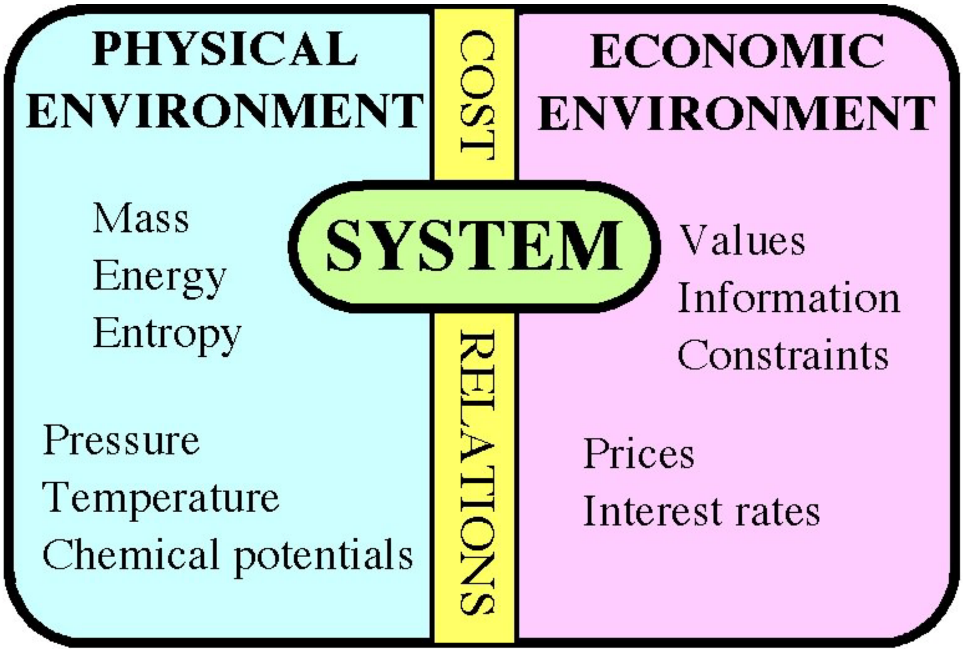

Figure 16 The system in two environments

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 relation 18, for a given product during its life time. Thus, the objective function is

$$\Phi_o = \mathrm{LCC} = \sum_{life\,time} C_{pr} = \sum_{life\,time} \left(C_{in} + C_{labor} + C_{capital} + C_{tax} - C_{aid} \right) \qquad (19)$$

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 become more competitive.

If we know the cost relations, we are able to link the physical and economic environments. The cost equations 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.

3.3 Thermoeconomic Accounting

Thermoeconomic accounting method is based on the pioneer works of Gaggioli and his co-workers as well as Tribus and his co-workers.

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 product, destruction 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, in the form of relation 18, 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 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 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, and a good start of an optimization procedure.

3.4 Thermoeconomic optimization

When constructing a system, the goal is often 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.

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_o, i.e., the total cost of the system or the product.

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

$$\Phi_o = \Phi_o(\{x_j\},\{y_k\},\{z_l\}) \tag{20}$$

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:

$$\Phi_j(\{x_i\},\{y_k\},\{z_l\}) \qquad j = 1, 2, \ldots, n \tag{21}$$

Thus, the optimization is formulated as follows:

$$\text{Minimize } \Phi_o = \Phi_o(\{x_i\},\{y_k\},\{z_l\}) \tag{22}$$

Subject to

$$\Phi_j(\{x_i\},\{y_k\},\{z_l\}) \qquad j = 1, 2, \ldots, n \tag{23}$$

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_o 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:

$$\theta_k = \frac{\Delta\Phi_o}{\Delta y_k} \qquad k = 1, 2, \ldots, m \tag{24}$$

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 19. 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.

4 EXERGETICS AND DESALINATION

A salt concentration of about 4.5% (weight) in sea water implies that 1 kg of seawater contains (1000 – 45)/18 ≈ 53.05 mol of water and 45/58.5 ≈ 0.769 mol of salt (NaCl), or 0.769 mol of Na^+ and 0.769 mol Cl^-, i.e., together about 54.59 mol (≈ 53.05 + 0.769 + 0.769). The molar weights of water and salt are 18 and 58.5 g, respectively. The mol concentration of water in sea water then becomes 0.972. Thus, at an ambient temperature of 30°C, fresh water represents an exergy amount of about 4 kJ/kg, from just the difference in concentration of salt,

$$E = RT_o \ln\left(\frac{c}{c_o}\right) \approx 8.314 \times (273.15+30) \times \ln\left(\frac{1}{0.972}\right) \approx 71.6\ [\text{J/mol}] \approx 4.0\ [\text{kJ/kg}] \tag{25}$$

In order to better understand this value let us compare with other forms of exergy for the same amount of water. As mechanical exergy this is equivalent to a height of about 400 m or a speed of about 320 km/hr. Thus, a considerable exergy effect. However, as thermal exergy it would represent a temperature increase of only about 5°C over the ambient temperature.

Let us also study desalination as a problem of information, see relation 8. Consider a container with an ideal mixture of two different particles, salt and water, see Figure 17. The total number of particles is N, divided into N_1 and N_2 respectively. The particle concentration then becomes $x_1=N_1/N$ and $x_2=N_2/N=1-x_1$.

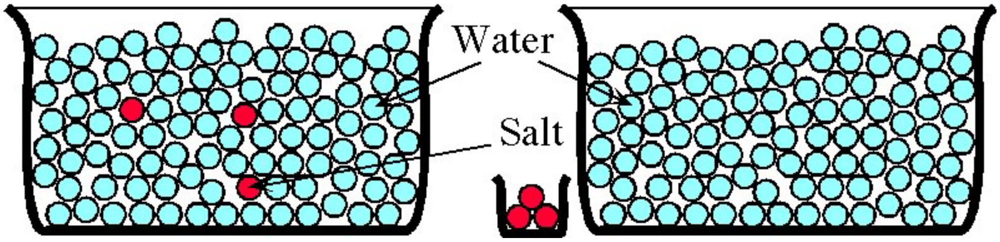

Figure 17 Seawater = Salt + Water.

If we pick one particle from the left container we face the probabilities $P_1=x_1$ and $P_2=x_2$ to get a specific molecule. From information theory we learn that the **information** or the **information capacity** I in binary unit [bit] is

$$I = \frac{1}{\ln 2}\left(\sum_{j=1}^{\Omega} P_j \ln P_j - \sum_{j=1}^{\Omega} P_j^o \ln P_j^o\right) \tag{26}$$

where Ω is the number of possibilities, P^o the probability at equilibrium, i.e., before we know what particle we get, and P the probability when we know, i.e., in this case P is 1.

The information we gain when we discover which molecule it is, then becomes

$$\Delta I = \frac{1}{\ln 2}\left[x_1 \ln\left(\frac{1}{x_1}\right) + x_2 \ln\left(\frac{1}{x_2}\right)\right] \tag{27}$$

Let us now add one container, and arrange the molecules so that one only contains salt particles and the other one only contains water particles, see the right hand side of Figure 17. If we now pick one molecule from a specified container, then we know which molecule we get, and our knowledge and information increase by 0. By mixing the particles information is lost, i.e., ΔI per molecule, which can be related to a loss of exergy as above, see relation 8. Let us assume that we have sea water with 4.5% (weight) of salt in the left container, then on the average about 2.8 of 100 particles (molecules) would be salt and the rest is water particles. Then, $x_1 = x_{Salt} = 2.8/100 = 0.028$ and $x_2 = x_{Water} = 972/100 = 0.972$, and the information carried by each particle becomes, accordingly:

$$\Delta I = \frac{1}{\ln 2}\left[x_{Salt} \ln\left(\frac{1}{x_{Salt}}\right) + x_{Water} \ln\left(\frac{1}{x_{Water}}\right)\right] = \frac{1}{\ln 2}\left[0.028 \ln\left(\frac{1}{0.028}\right) + 0.972 \ln\left(\frac{1}{0.972}\right)\right] \approx \tag{28}$$

$$\approx 0.028 \times 5.16 + 0.972 \times 0.0410 \approx 0.184 \text{ [bits]}$$

As we would expect the salt particles carries more information with it than the water particles, because of its scarcity, i.e., 5.16 and 0.0410 bits respectively. Note that, x_1 and x_2 are just weighting factors for the contributions of the different particles to the total information.

The exergy needed to pick only water molecules from a mixture of constant mixture, 4.5% salt and at 30°C then becomes, see relation 8:

$$E = RT_o \ln 2 I = RT_o \ln 2 \times \frac{1}{\ln 2}\left[1 \times \ln\left(\frac{1}{x_2}\right)\right] = RT_o \ln\left(\frac{1}{x_2}\right) \tag{29}$$

which is exactly the same expression as in relation 25, since

$$\frac{c}{c_o} = \frac{1}{x_2} \tag{30}$$

Thus, there is a fundamental correspondence between the problem of desalination in thermodynamics, or rather classical thermodynamics, and in information theory, or rather statistical mechanics.

4.1 The Multistage Flashing Process

The Multistage Flash (MSF) distillation process is shown in Figure 18. The temperature and exergy profiles are also illustrated, and will be further discussed. The process is divided into brine heater and heat recovery. In the brine heater, which is a heat exchanger, exergy is added to the brine by the condensation of steam. The heat recovery is made up of a series of stages, in which vapor is flashed and condensed, i.e., distilled. The distillate is then carefully collected, throughout the process, and the heat from the condensation of the distillate heats the feed water. In this process the seawater passes through without recirculation.

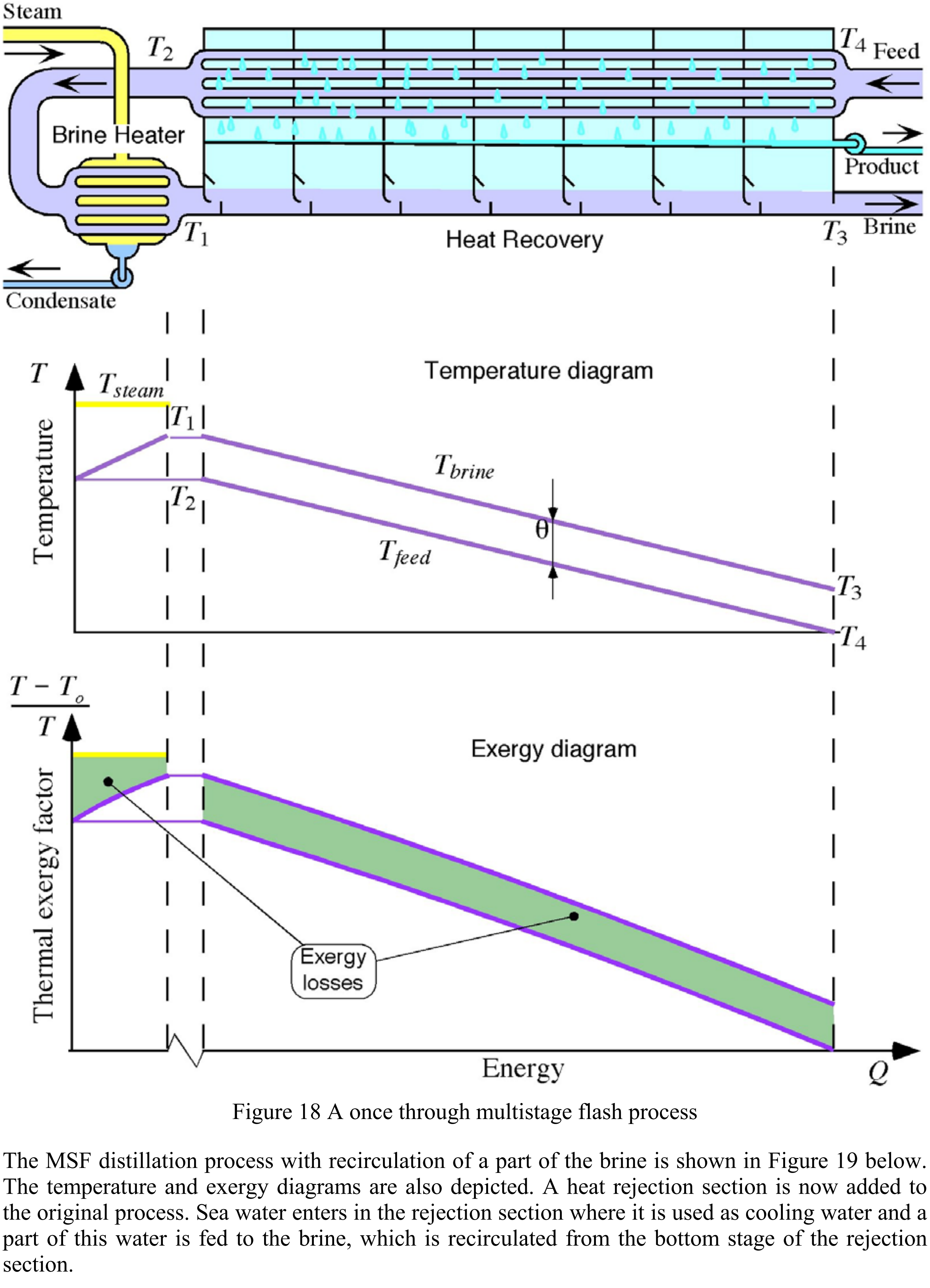

Figure 18 A once through multistage flash process

The MSF distillation process with recirculation of a part of the brine is shown in Figure 19 below. The temperature and exergy diagrams are also depicted. A heat rejection section is now added to the original process. Sea water enters in the rejection section where it is used as cooling water and a part of this water is fed to the brine, which is recirculated from the bottom stage of the rejection section.

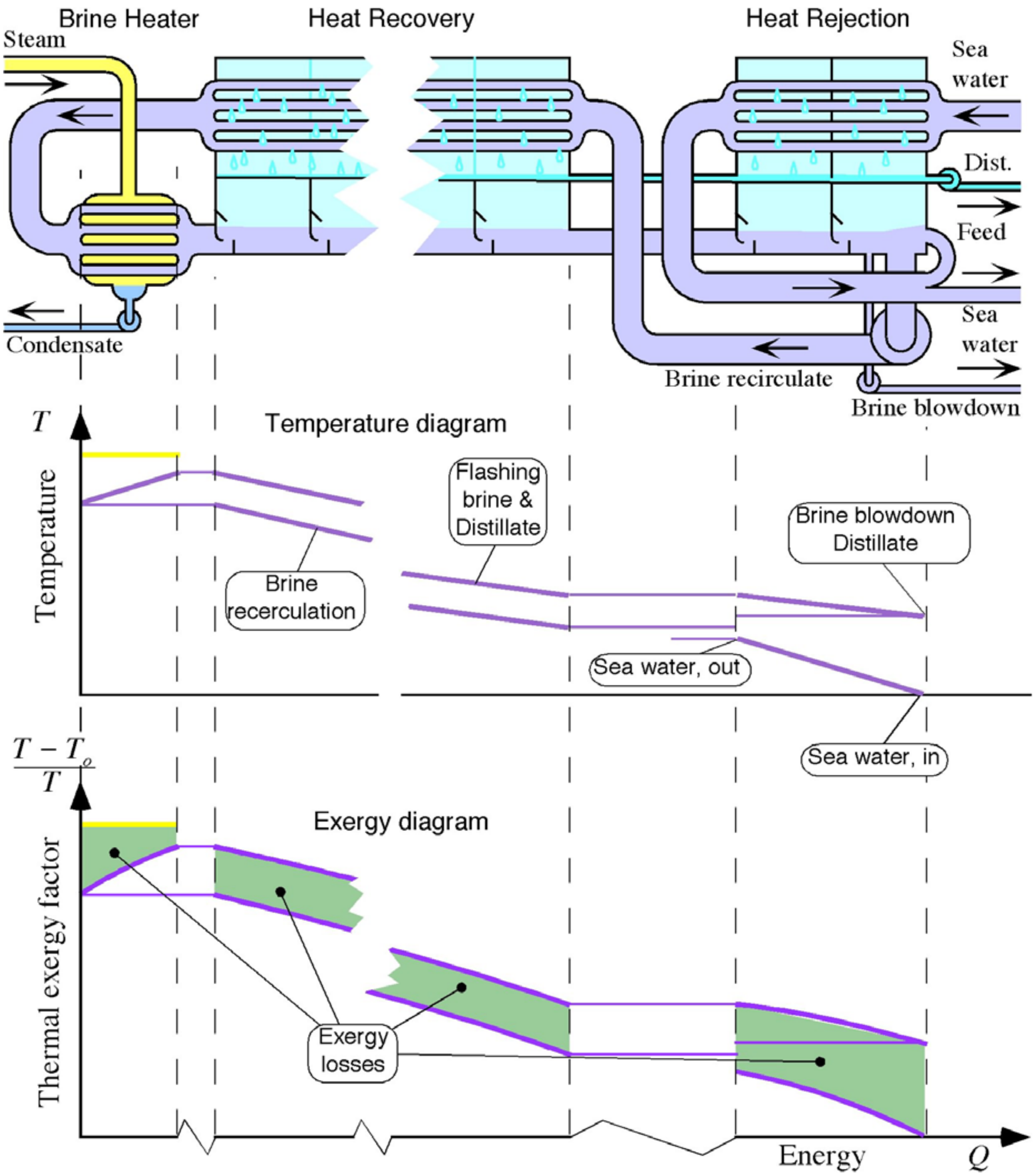

Figure 19 A brine recirculation multistage flash process

4.1.1 Exergy Flows in the Brine Heater

Let us now look closer into the exergy use in the process and relate this to the common practice in the field. The thermal exergy consumption is usually expressed by the performance ration *R*,

$$R = \frac{M_d}{M_s} \tag{31}$$

where M_d is the distillate flow rate and M_s is the steam flow rate to the brine heater, see Figure 20 below. By multiplying with the latent heat of vaporization of water in the numerator and the denominator, this ratio is also related to energies, i.e., an energy performance ration.

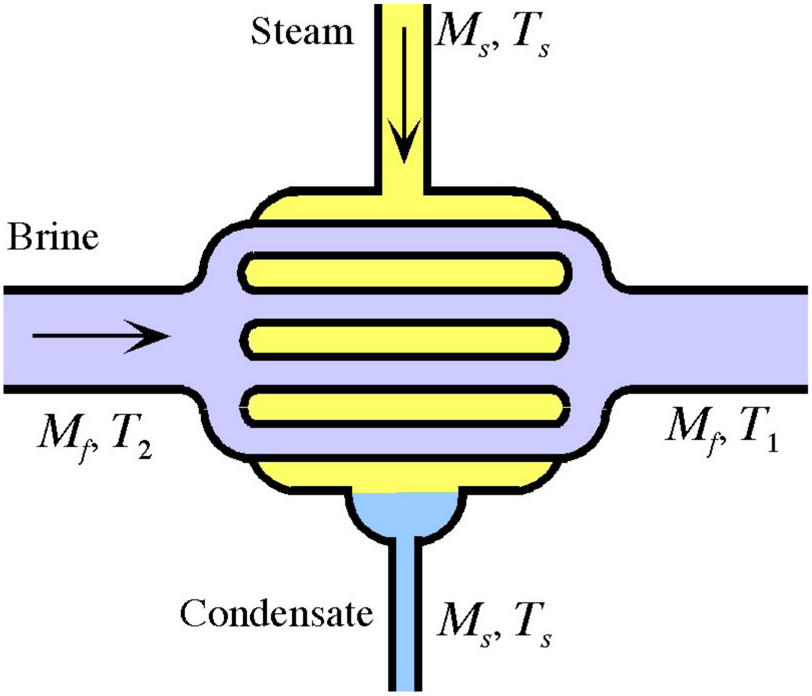

Figure 20 The brine heater, with indicate mass flow rates and temperatures

If we assume no energy losses, then all thermal energy from the condensation of the steam, ΔQ_s will be transferred as increase of thermal energy of the feed, ΔQ_f, i.e., energy conservation, $\Delta Q_s = \Delta Q_f$, and we have,

$$\Delta Q_s = \lambda M_s = \Delta Q_f = c_p M_f \theta \tag{32}$$

where λ is latent heat of vaporization of water, c_p is the specific heat of the brine and θ is the temperature rise of the brine, i.e., $T_1 - T_2$. The performance ratio may now be written,

$$R = \frac{M_d}{M_s} = \frac{\lambda M_d}{c_p M_f \theta} = \frac{\lambda}{c_p \theta} \frac{M_d}{M_f} \tag{33}$$

The thermal exergy released from the condensation of the steam, ΔE_s is

$$\Delta E_s = \lambda M_s \left(\frac{T_s - T_o}{T_s} \right) \tag{34}$$

where $(T_s - T_o)/T_s$ is the exergy or Carnot factor for the steam. This exergy does not include the exergy from the sensible heat, i.e., the exergy of the condensate with respect to the ambient temperature T_o, nor the chemical exergy of water.

The exergy of the sensible heat of the feed is

$$E_f = c_p M_f \left(T_f - T_o - T_o \ln \frac{T_f}{T_o} \right) \tag{35}$$

Thus, the increase of thermal exergy of the feed, ΔE_f as it passes through the brine heater and the temperature increases from T_2 to T_1 then becomes

$$\begin{aligned} \Delta E_f &= E_f(T_1) - E_f(T_2) = c_p M_f \left(T_1 - T_o - T_o \ln \frac{T_1}{T_o} \right) - c_p M_f \left(T_2 - T_o - T_o \ln \frac{T_2}{T_o} \right) = \\ &= c_p M_f \left(T_1 - T_2 - T_o \ln \frac{T_1}{T_2} \right) \end{aligned} \tag{36}$$

The exergy flows through the brine heater may be illustrated by a flow diagram, see Figure 16. The width of the flows indicates the amount of exergy, and the exergy destruction from irreversibilities, ΔE is exergy outflow minus exergy inflow, i.e.,

$$\Delta E = \Delta E_s + E_f(T_2) - E_f(T_1) = \Delta E_s - \Delta E_f \tag{37}$$

As we see the exergy efficiency, defined as useful exergy outflow divided by total exergy inflow, see relation 12, is very high, or about 90% for real plants.

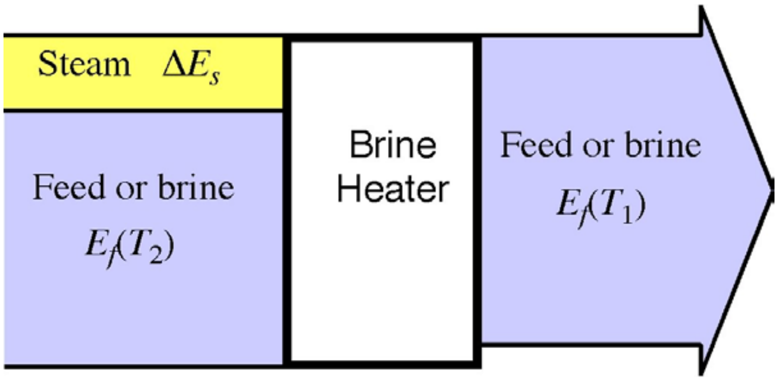

Figure 21 The exergy flow through the brine heater

The exergy transfer can also be illustrated by an exergy diagram or an energy utility diagram, see Figure 21. In this diagram the exergies are represented by areas. The temperature diagram at left hand side of Figure 22 is just to show the similarities with and links to a temperature – enthalpy diagram. From the exergy diagram we see how most of the thermal exergy in the steam, ΔE_s is transferred into thermal exergy in the feed or brine, ΔE_f, where the difference, $\Delta E_s - \Delta E_f$, is defined as the exergy destruction of the process, ΔE. These diagrams, offers a better insight to the process, thus, are more useful in an optimization process.

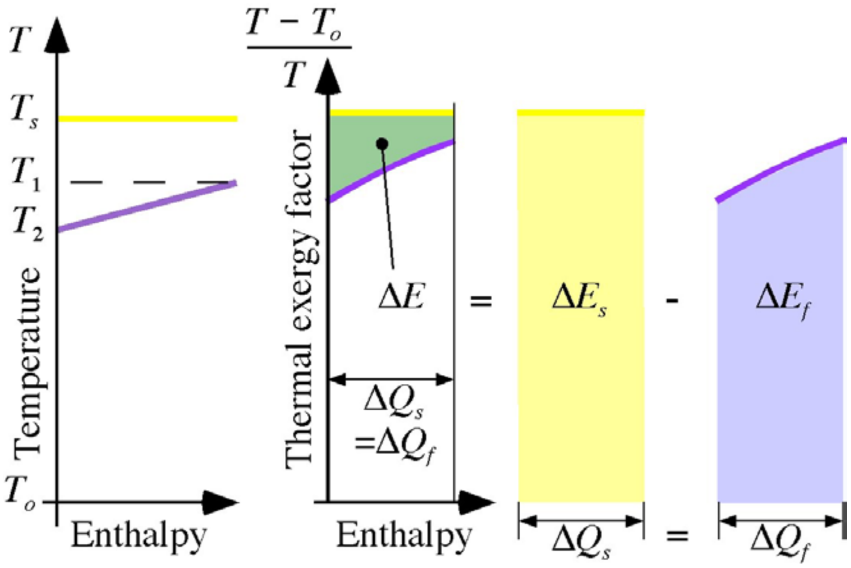

Figure 22 Exergy diagram of the brine heater

4.1.2 Exergy Flows in the Heat Recovery and the Heat Rejection Section

The heat recovery and heat rejection section is similar to a counter flow heat exchanger, except for the production of the distillate, see Figure 23 below, which relates to the once through multistage flash process.

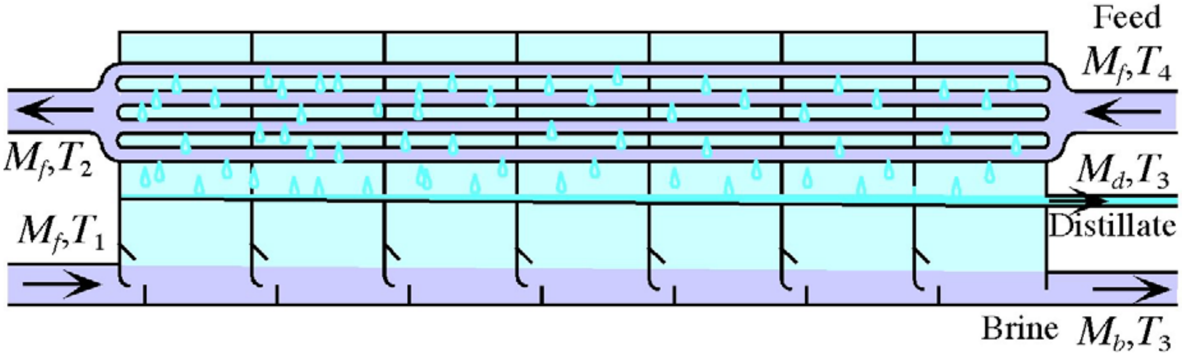

Figure 23 The heat recovery, with indicate mass flow rates and temperatures

From conservation of mass we have that $M_f=M_b+M_d$. If we assume no energy losses, then from conservation of energy all thermal energy released from the brine and the distillate, $\Delta Q_b+\Delta Q_d$ will end up as an increase of the thermal energy of the feed, ΔQ_f, i.e.,

$$\Delta Q_b + \Delta Q_d = \Delta Q_f \tag{38}$$

or

$$\begin{aligned} &c_p M_b (T_1 - T_3) + c_p M_d (T_1 - T_3) = c_p M_f (T_2 - T_4) \\ &c_p M_f (T_1 - T_3) = c_p M_f (T_2 - T_4) \\ &T_1 - T_3 = T_2 - T_4 \\ &T_1 - T_2 = T_3 - T_4 = \theta \end{aligned} \tag{39}$$

This is also illustrated as parallel lines in the temperature diagram in the Figure 18, above.

Assume that the heat is only transferred by means of heat convection, i.e., when the distillate evaporates from the brine and condensate on the tubes carrying the feed. Thus, the distillate can be regarded as a carrier of heat from brine to feed. Then, the total amount of heat transferred, ΔQ_f, must be equivalent to the total amount of heat in evaporation or condensation, i.e., the latent heat carried by the distillate, ΔQ_d, thus we have

$$\Delta Q_f = c_p M_f (T_1 - T_3) = \Delta Q_d = \lambda M_d \qquad (40)$$

From an energy point of view we see that everything is in balance, however, from an exergy point this is not the case. All thermal exergies relates to sensible heat and can now be treated the same way as for the feed in the brine heater, above. However, we also have to consider the chemical exergy of the distillate. Assume the feed water entering at ambient temperature, i.e., $T_4=T_o$, then the exergy of the feed is zero by definition. The thermal exergies of the feed, brine and distillate are that of sensible heat, i.e.,

$$E_f = c_p M_f \left(T_f - T_o - T_o \ln \frac{T_f}{T_o} \right) \qquad (41)$$

The chemical exergy of the distillate is about 4 kJ/kg at a sea water content of 4.5% salt. A typical exergy flow diagram may then look as in Figure 24.

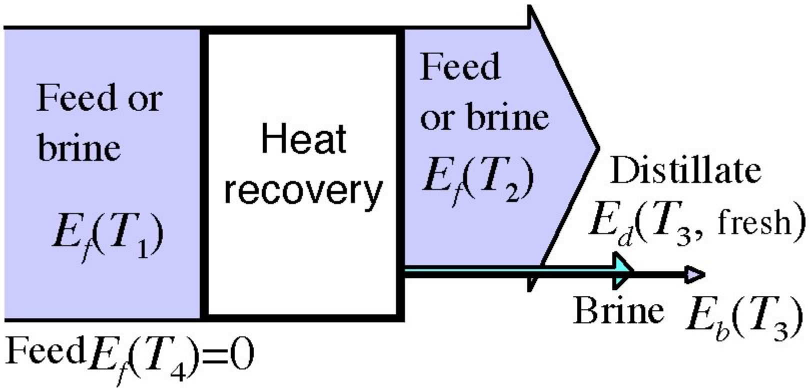

Figure 24 The exergy flow through the heat recovery

As we can see, the exergy of the distillate is a small part, however, the feed or brine output is an input in the brine heater, see above. Thus, if we combine these two processes, the internal recycling of heat in the total process becomes more obvious, see Figure 25.

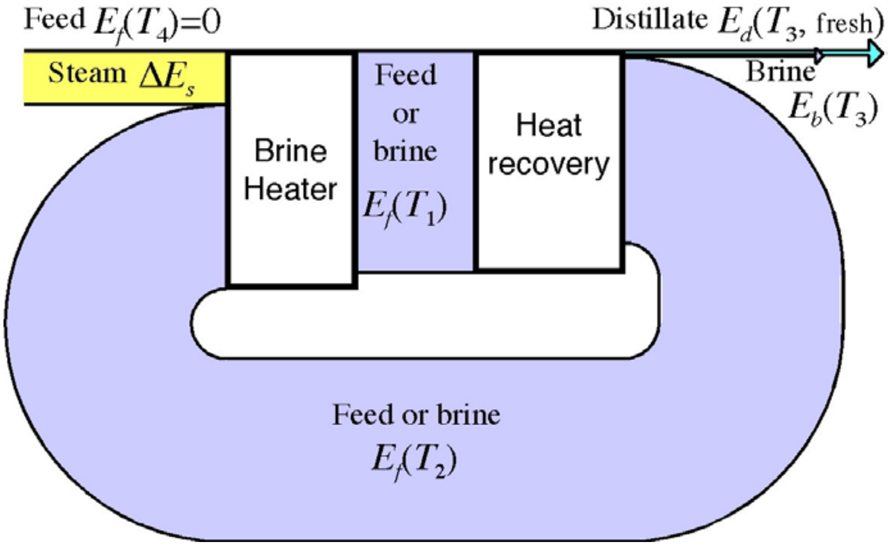

Figure 25 The exergy flow through the brine heater and the heat recovery

The exergy diagram of the heat recovery is found in the bottom part of Figure 18 and Figure 19, respectively. The calculation of these diagrams is analogous to that for the exergy diagram of the brine heater.

The exergy of the input steam in present MSF plants is at least about 10 times the exergy of the distillate, or about 40 kJ/kg of distillate, which is partly explained by the enormous recycling of exergy in the process. However, in addition to the steam input we also have exergy for pumping and for maintaining vacuum of about 10 and 4 kJ/kg of distillate, respectively. Thus, the total exergy output as distillate is usually only about 5 to 7% of the total exergy input.

4.2 The Multiple Effect Boiling Process

The Multiple Effect Boiling (MEB) distillation process is shown in Figure 26. This process is similar to the MSF process, since it uses exergy for heat, pumping and for creating and maintaining vacuum in the evaporators. In principal, all exergies can be calculated from the relations used for the MSF process. However, due to varying conditions we can not simplify the description, as we did for the MSF process. A schematic temperature diagram of the process is depicted in Figure 26.

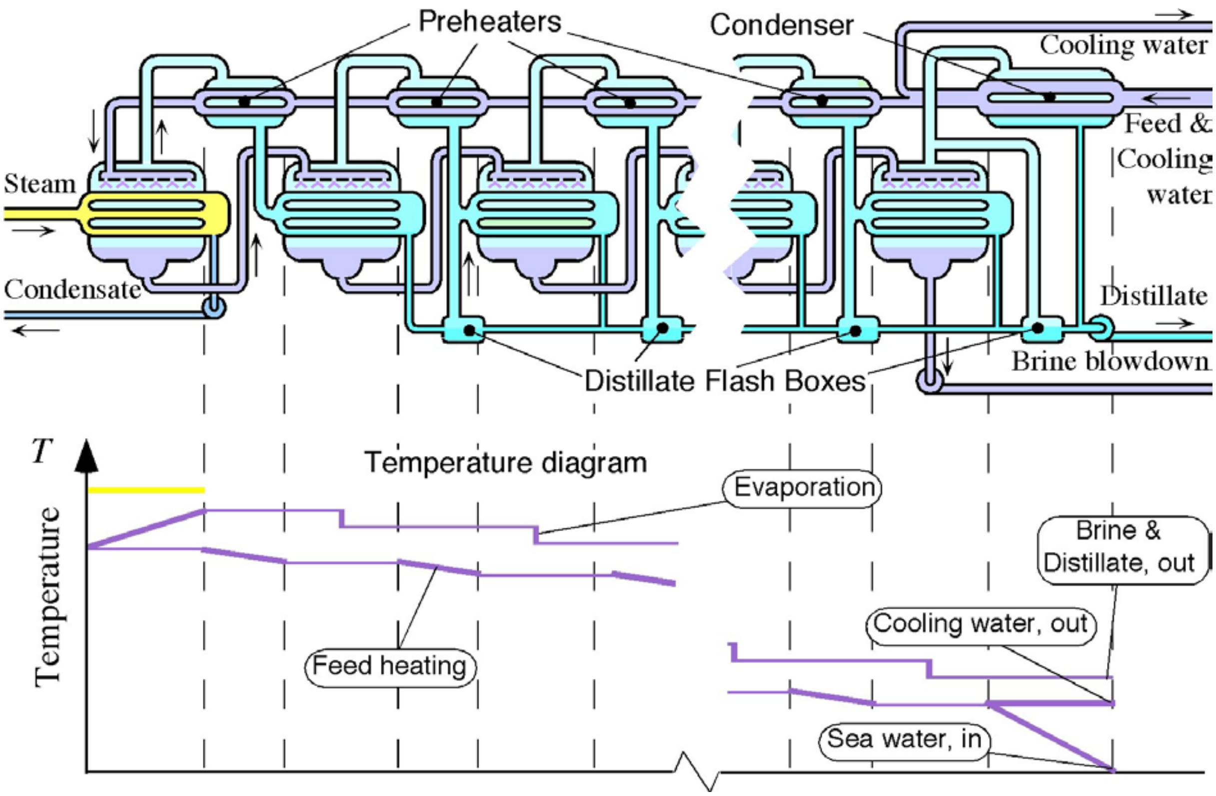

Figure 26 A multiple effect boiling process

The thermal exergy flows through one effect, see Figure 26, can be calculated according to the following relations:

For latent heat: $E_{latent} = \lambda M \left(\frac{T - T_o}{T} \right)$ (42)

For sensible heat: $E_{sensible} = c_p M \left(T - T_o - T_o \ln \frac{T}{T_o} \right)$ (43)

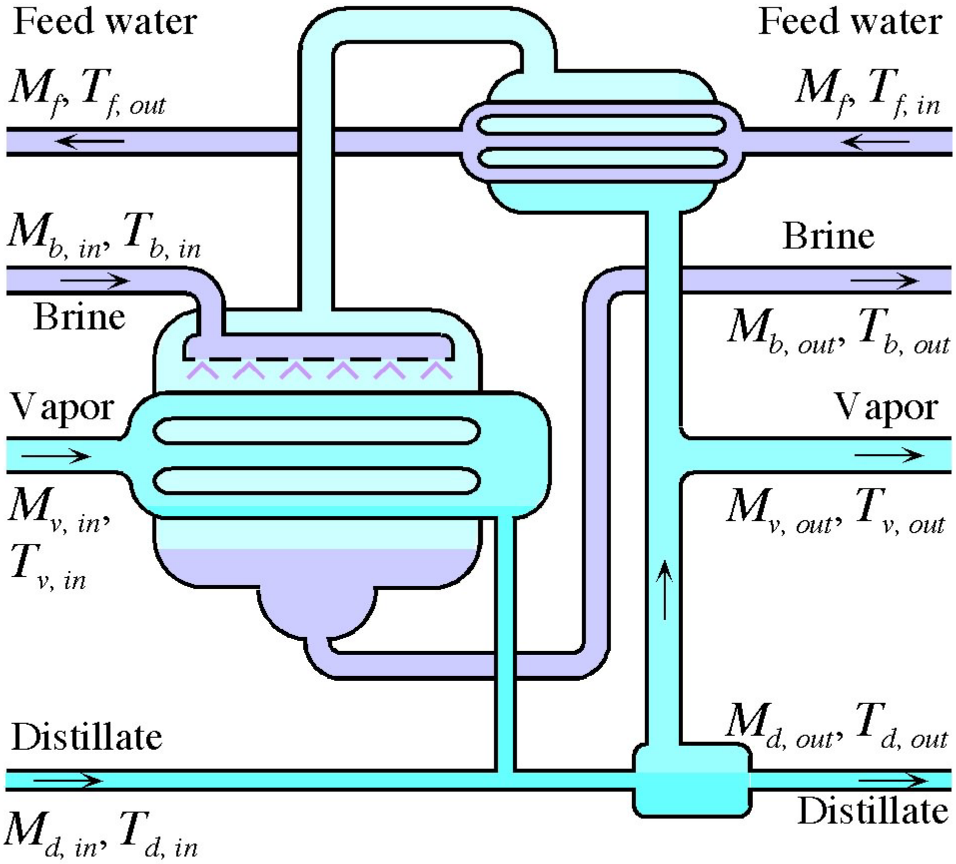

Figure 27 The effect of a multiple effect boiling process

From given data a complete exergy flow diagram can be calculated, see Figure 28, which refers to typical values for one effect of a MEB process. As in the MSF process, the exergy output as gain of distillate is only a fraction of the total turnover. This partly explains the low exergy efficiency, defined as exergy increase of distillate divided by net exergy use, see relation 13, of about 10%.

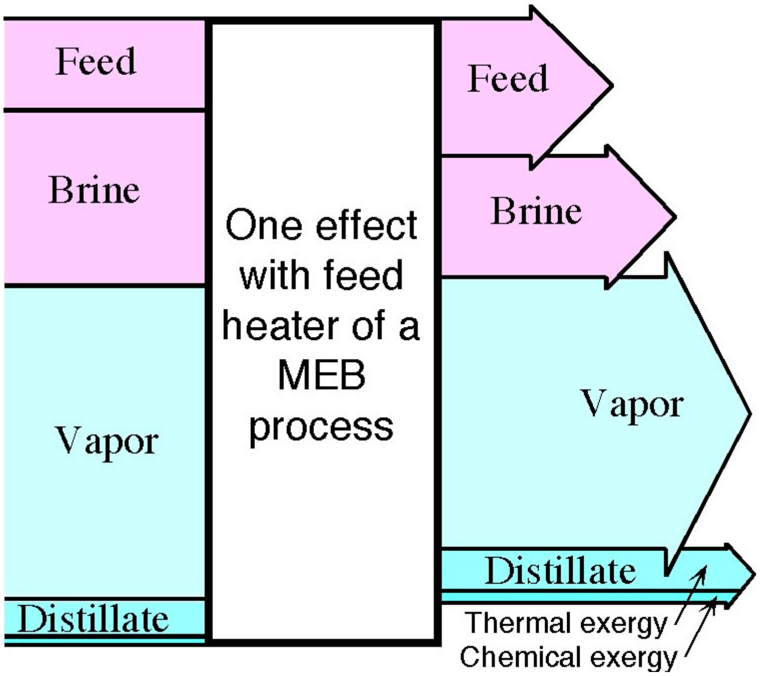

Figure 28 The exergy flows of one effect with feed heater of a multiple effect boiling process

An exergy diagram of the one effect MEB process is outlined in Figure 29. The thermal exergy factor for the incoming exergy is always higher than for the outgoing exergy, and the difference between the two areas defines the exergy destruction, i.e., irreversibilities.

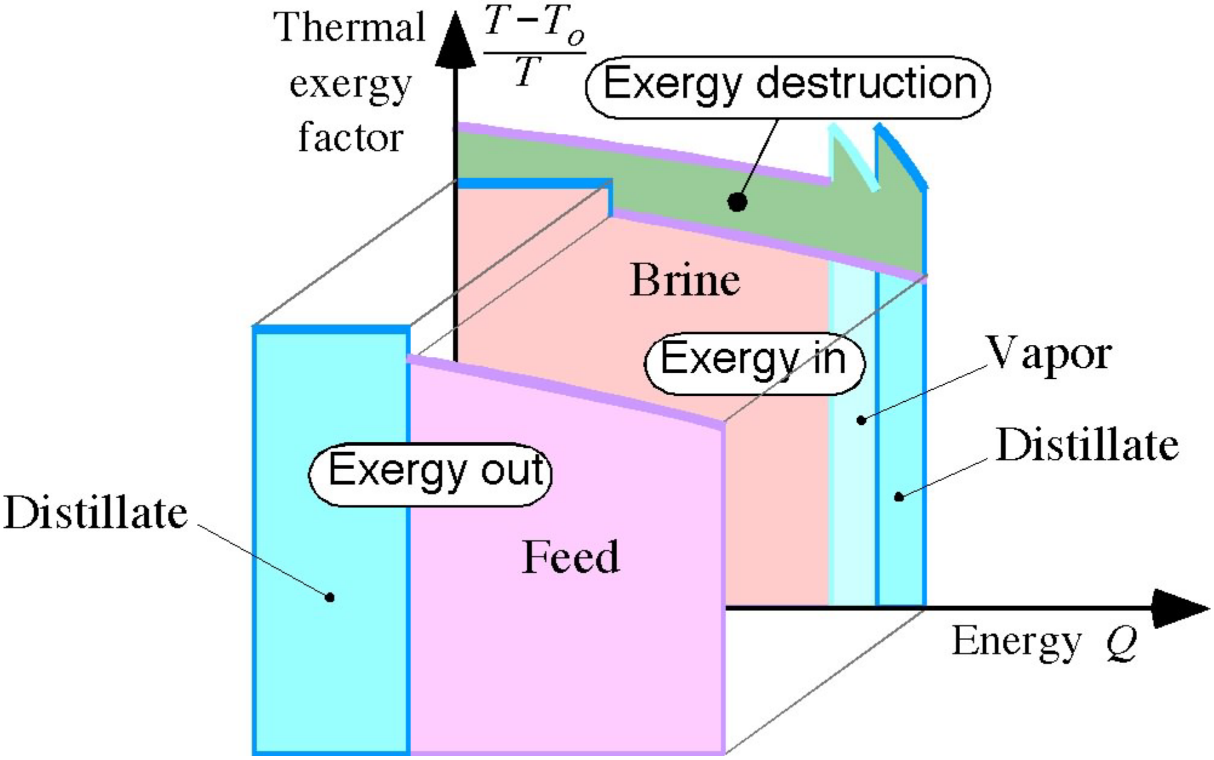

Figure 29 The exergy diagram of one effect with feed heater of a multiple effect boiling process

The exergy of the input steam in present MEB plants is about 7 to 10 times the exergy of the distillate, or about 30-40 kJ/kg of distillate, and in addition exergy for pumping and for maintaining vacuum of about 10 and 4 kJ/kg of distillate, respectively. Thus, the total exergy output as distillate is usually less than 10% of the total exergy input.

4.3 The Reverse Osmosis Process

Osmosis is what makes two mixtures of different composition to unite into the same composition. This is a good example of diffusion, i.e., that a substance always goes from a region of relatively high concentration to one of lower concentration, or the natural law that everything disperse, see Table 1. A semi-permeable membrane allows water to pass through, but not the salt. If the membrane is placed vertically, see Figure 30, a pressure *P* must be applied to keep the water from entering the brine.

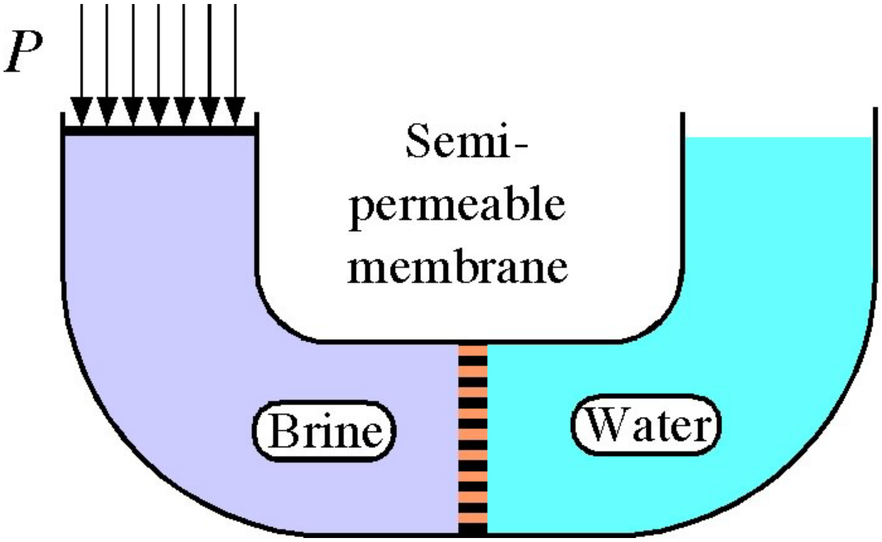

Figure 30 The osmotic force in action

This pressure corresponds exactly to the exergy of the system. If we want to produce fresh water from sea water we have to apply at least this pressure, and perform a work *W*, see relation 2, which is equivalent to the exergy *E* of the product, i.e.,

$$W = PV = E \tag{44}$$

where *V* is the volume of fresh water produced. At 4.5% of salt in the sea water and an assumed density of 1000 kg/m^3 the pressure becomes:

$$P = \frac{E}{V} \approx \frac{4000 \times 1000}{1} \left(\frac{\mathrm{J}}{\mathrm{m}^3}\right) \approx 4.0(\mathrm{MPa}) \tag{45}$$

or 40 bar. Thus, to produce fresh water from sea water, we need to at least exceed this pressure, in a so called reverse osmosis process (RO). Usually pressures of about 60 to 80 bars are used to permeate 20 to 30 % of the feed water. This could be visualized accordingly: first the feed water is pumped up to a pressure, equivalent to about 800 m of height, needed for water molecules to permeate through the membrane, the reject water of higher salinity is then allowed to “fall down” and generate shaft work via a recovery turbine, see Figure 31. In real plants this is usually done in more than one stage.

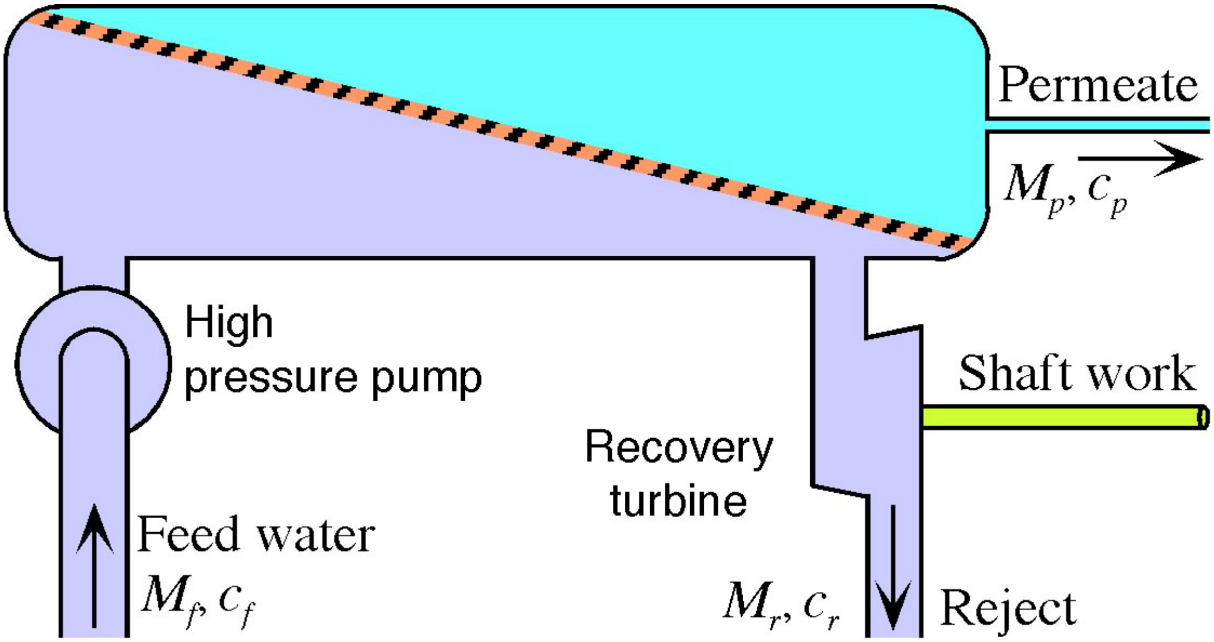

Figure 31 A reverse osmosis process with work recovery

Exergy only appears in the form of concentration and pressure, for which the following relations hold:

$$E_{concentration} = \left| nRT_o \ln\left(\frac{c}{c_o}\right) \right| \tag{46}$$

$$E_{pressure} = V(P - P_o) \tag{47}$$

where we assume water to be incompressible. The absolute sign has been added to avoid negative exergy values for the reject, where the concentration of salt increases, i.e., the concentration of water c decreases below c_o. An exergy flow diagram of a real process with two RO stages is depicted in Figure 32 below.

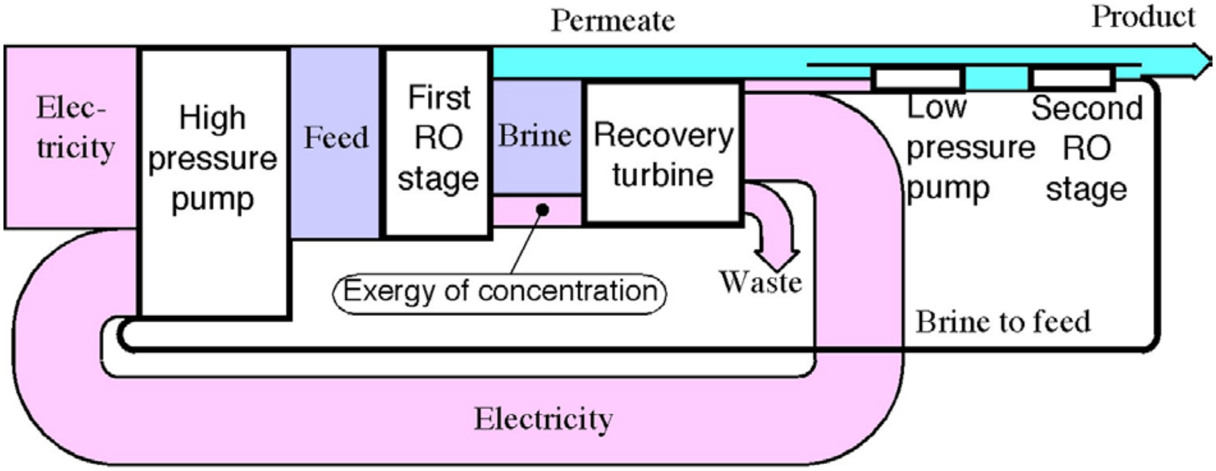

Figure 32 The exergy flow of a two stage RO process with recovery of electricity

A considerable amount of electricity is being regenerated by the recovery unit, this improves the exergy efficiency from about 9 to 16%. The exergy as increased concentration of salt in the brine, however, is not being utilized, instead it becomes an exergy waste flow of about the same amount as the product. The exergy need for RO plants with recovery units is usually about 25 kJ/kg of product, i.e., an exergy efficiency of 16%, which is among the highest for real desalination processes.

Acknowledgment:

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

SUMMARY:

Exergy is a useful concept since it is a link between the physical and engineering world and the surrounding environment. Exergy expresses the true efficiency of engineering systems, which makes it a useful concept to find possible improvements. In systems where energy appears in many different forms, e.g. thermal, chemical and mechanical, this is particularly important. Therefor, exergy is a very useful concept in the design of engineering systems, especially desalination processes.

Exergy is *the* “fuel” for systems that are sustained by converting energy and materials, i.e. metabolic or dissipative processes, e.g. a living cell, an organism, an eco-system, the earth’s surface with its material cycles, or a society. If these systems are sustained only by renewable resources they may also be regarded as sustainable and exergy is a suitable concept to describe such systems scientifically. The solar powered desalination processes that occur in green plants are sustainable.

The exergy concept has mostly been used within heat and power technology, where one works with thermal energy of varying qualities. However, the field of application is gradually increasing to the totality of energy, material and information conversions in the society, e.g. Life Cycle Assessment or Life Cycle Analysis (LCA) and Environmental Economics. This yields a uniform description of the use of physical resources and the environmental impacts in connection with this use.

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, including desalination plants. By adopting the methods of exergy flow diagrams and LCEA new technology of a sustainable society could be further developed.

Reverse osmosis processes offer the highest exergy efficiency of present desalination techniques. However, MSF and MEB processes can be combined with a power production process, where the waste heat is used for the desalination process.

GLOSSARY

Deposit. Non-renewable resource.
Energy. Motion, or ability of motion.
Entropy. A concept of disorder.
Exergetics. Theory of exergy and its applications.
Exergy. Work, i.e. ordered motion, or ability of work.
Exergy Analysis. Calculation of the total exergy input to a product or service.
Exergy Destruction. Lost exergy in a process.
Fund. Resource maintained by a natural resource flow.
Information. Capacity of carrying a message.
Irreversibility. Pure entropy, i.e. no exergy, or energy at reference state.
Life Cycle Analysis. Method to calculate the total environmental effect of a product or service.
Life Cycle Exergy Analysis. Method to calculate the total effect of a product or service in terms of exergy and with respect to use of non-renewable resources.
Thermoeconomics. A method that combines thermodynamics and economy in order to improve engineering systems by the use of accounting or optimization procedures.

NOMENCLATURE:

c	speed of light in vacuum, 2.997925×10^{8} (m/s)
c	concentration
c_p	specific heat
C	cost (monetary unit)
E	exergy (J)
E^{tot}	total exergy (J)
E_{in}	exergy input (J)
E_{out}	exergy output (J)
E_{waste}	exergy of waste (J)
E_{pr}	exergy of product (J)
E_{tr}	transiting exergy (J)
I	information (bit)
j	unit, j=1, 2,…, n
k	Boltzmann constant, 1.38054×10^{-23} (J/molecule K)
k	unit, k=1, 2,…, m
l	unit, l=1, 2,…, r
m	mass (kg)

M_b	brine mass flow rate (kg/s)
M_d	distillate mass flow rate (kg/s)
M_f	feed mass flow rate (kg/s)
M_s	steam mass flow rate (kg/s)
N	Avogadros number, 6.022×10^{23} (molecule/mol)
N	number of particles
P	pressure (Pa)
P	probability
P^o	probality at equilibrium
Q	heat (J)
R	gas constant, 8.314 (J/mol K)
R	performance ration, $R = M_d / M_s$
S	entropy (J/K)
S^{tot}	entropy of the total system, i.e., the system and the environment (J/K)
S_{eq}	entropy at equilibrium state (J/K)
t	time (s)
T	temperature (K)
T_o	temperature of the environment (K)
U	(internal) energy (J)
V	volume (m^3)
W	work (J)
x	state variable
x	concentration
y	decision variable
z	decision parameter
ΔE_i	exergy destruction in process i (J)
Φ_o	objective function
Φ_j	state equation
λ	latent heat of vaporization of water
η_{ex}	exergy efficiency ($= \eta_{ex,2}$)
$\eta_{ex,1}$	exergy efficiency ($= E_{out} / E_{in}$)
$\eta_{ex,2}$	exergy efficiency ($= E_{pr} / E_{in}$)
$\eta_{ex,3}$	exergy efficiency ($= (E_{pr} - E_{tr}) / (E_{in} - E_{tr})$)
μ	chemical potential
θ_k	marginal cost, ($= \Delta\Phi_o / \Delta y_k$)
θ	temperature rise, ($=T_1 - T_2$)
Ω	number of possibilities

LCC	Life Cycle Cost
LCEA	Life Cycle Exergy Analysis
MEB	Multiple Effect Boiling
MSF	Multistage Flashing
RO	Reverse Osmosis

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