On Exergy and Sustainable Development in Environmental Engineering

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Abstract: Humankind faces the most serious challenge ever – sustainable development. A new paradigm based on respect of nature and awareness of natural mechanisms is needed. The concept of exergy and exergy based methods offers a unique potential to support this. Applications to real problems and possible solutions related to environmental engineering are presented.

Keywords: Exergy, environmental engineering, sustainable development.

INTRODUCTION

The evolution of knowledge is essential to human cultures. Every human culture carries a unique cultural paradigm—the soil for knowledge to grow and flourish. The diversity of cultures in our world is essential to the evolution of human knowledge—our creative diversity. This diversity is the wellspring of our progress and creativity.

Present focus must be on relationships; between humans and with nature. Today these relationships are too often characterized by greed and violence fostered by the present cultural paradigm, or arrogance and ignorance instead of friendship and compassion. This must change into a culture of peace. Peace within us, peace among us and peace with nature are essential for happiness, harmony and knowledge to flourish.

We, the people of the world, are also children of Earth with a common goal to care for life itself. We were given intelligence, emotions and possibilities, but also responsibilities. With these gifts we have created a world of prosperity, but also of poverty. The world has brought us together, but also apart and away from nature. We face a future of threats and limitations, but also possibilities. These challenges demand careful and responsible actions from everyone, based on a better understanding together with moral obligations.

The ongoing depletion of nature's capital must come to an end before it is too late. Values are lost and substances are spread in the environment when nature's capital is exploited and consumed by our economies. The physical conditions in nature change and create instability. New life forms that are better fitted to these new conditions will appear, i.e. *survival of the fittest*. Some of these new organisms will not support present higher forms of life, e.g. homo sapiens. We see this as new diseases. The avian influenza and the swine virus are just but two examples of an ongoing creation of new organisms that will go on as long as suitable conditions are offered. Thus, present industrial society is fertilizing its own extinction. The only solution to sustainable development for humankind is to restore and preserve nature's capital. This enforces a new paradigm based on increasing the capital of nature instead of exploiting it. Present technology and social management are founded, to a large extent, on the knowledge offered by science. Yet it is precisely these structures and their impact, which we know to be unsustainable. This implies tremendous efforts by the academia, which gradually adopts the new situation. In some areas of science this even relates to a complete change of paradigm. Science is partly the problem as well as a part of the solution for a sustainable development.

NATURE

Nature is the only creator and holder of life, as far as we know. From our understanding there are some fundamental conditions that maintain this unique capacity of nature.

CONTRAST, MOTION, EXERGY, AND TIME

In order for things to happen, i.e. motion to occur, there must be a driving force: something that can create action. A force is created by a difference in space of some kind, i.e. a contrast. This is a physical quantity such as temperature, pressure or tension. When this force, due to a contrast, is acting, it is also partly lost as irreversibility. This depletion is the creator of time. Thus, by allowing a contrast enclosed by the three-dimensional space to act, a new fourth dimension is created, i.e. time.

Exergy is the physical concept of contrast, which quantifies its power of action. A system in complete equilibrium with itself and the environment does not have any exergy, i.e. no power of action. Exergy is defined as work, i.e. ordered motion, or ability to perform work. Time is experienced when exergy is destroyed, i.e. a irreversible process, which creates a motion in a specific direction, i.e. in the direction of time.

The limited speed of light is also of essential importance for the life support systems. If light could move at infinite speed, the sun could, in principal, release all its stored exergy immediately, thus, there would be no time for life to appear. The light from other stars in the universe brings also with it the history, due to the limited speed of light. When we look into space, we look into the history of the universe.

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Table 1. Energy Versus Exergy

Energy	Exergy
The first law of thermodynamics	The second law of thermodynamics
Energy is motion or ability to produce motion.	Exergy is work, i.e. ordered motion, or ability to produce work.
Energy and matter is “the same thing.”	Exergy and information* is “the same thing.”
Energy is always conserved, i.e. in balance; it can neither be produced nor consumed.	Exergy is always conserved in a reversible process, but reduced in an irreversible process, i.e. real processes. Thus, exergy is never in balance for real processes.
Energy is a measure of quantity.	Exergy is a measure of quantity and quality.

*as defined in information theory [1].

The border of the universe gives us its time of birth, or the so-called “big bang,” perhaps the birth of time. However, if the universe is infinite, then also time would be infinite.

Energy, Matter, Exergy, and Entropy

Energy and matter cannot be created, destroyed, produced or consumed. Energy and matter can only be converted into different forms. This occurs by the consumption of contrast. Locally, the contrast may increase, but this can only occur at the expense of an even greater deterioration of the contrast elsewhere. On the whole it is a question of continuous deterioration of contrast, thus, pointing out the existence and direction of time, see Fig. (**1**).

Energy and/or matter flow through a system. The motive force of the flow of energy and/or matter through the system is the contrast or the level of order. Energy and/or matter are falling from high order, i.e. low entropy, in the inflow into low order, i.e. high entropy, in the outflow. This is also expressed as a destruction of exergy [1-3].

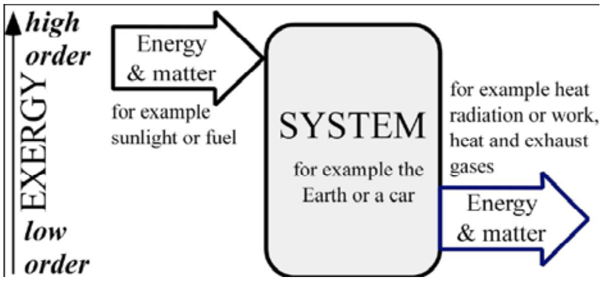

Fig. (1). The flow of energy and matter through a system.

Energy and matter only serve as carriers of contrast, which is partly consumed when it flows through a system. When energy and matter flow through a system, a very small part of this may sometimes be stored in or removed from the system. If there is a balance between inlets and outlets of energy and matter, the system will remain unchanged, a kind of steady state that is described in Fig. (**1**). Such steady state systems are the moon and a car. The moon offers us moonlight and a car is a mean of transport, however, the systems remain in principal unchanged. Table **1** summarizes some thermodynamic differences between energy and exergy.

If exergy is stored in the system we may have a viable state, i.e. life may occur. Logic would suggest therefore that the existence of life and the evolution of life imply that exergy from the sun must be stored on Earth.

Fig. (2). The Sun-Earth-Space system.

Earth, the Sun, and Space

The source of exergy on Earth is secured from the contrast between the sun and space, see Fig. (**2**). The exergy on Earth, exists through the conversion of energy from sunlight into heat radiation, which flows from Earth back into space. Due to this, all flows of energy and matter are carried forward through systems on Earth’s surface, and life can be created and maintained.

Life

Life in nature relates to three fundamental processes: production, consumption, and decomposition. These maintain the circulation of matter by using the incoming solar exergy in a sustainable and evolutionary way, see Fig. (**3**).

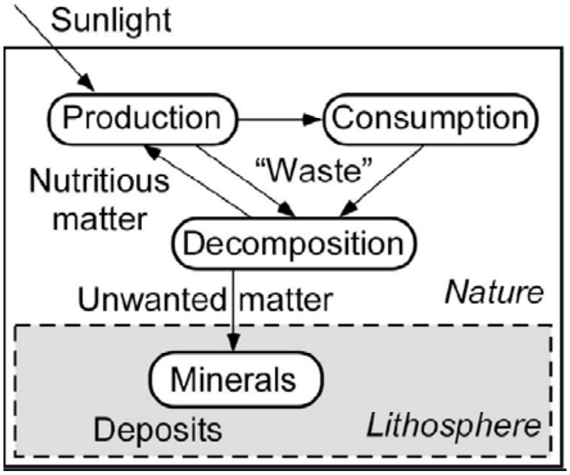

Fig. (3). The circulation of matter in nature is powered by sunlight.

Green plants, which represent the production process, convert exergy from sunlight into the exergy-rich matter of biomass, via photosynthesis. The exergy as biomass then passes through different food chains in the ecosystems. At every trophic level exergy is consumed and decomposition organisms dominate the last level in this food chain. There is no waste, however a removal of "unwanted" substances. Nature operates a unique machinery of development on Earth by capturing and sealing certain substances into minerals in Earth's crust. A fraction of the exergy from the sun-space contrast is stored as an increase of the exergy capital on Earth. This appears as a net-flow of "unwanted" substances from the biosphere into the lithosphere as well as a redistribution of other substances in the environment, e.g. oxygen to the atmosphere. Thus, the exergy capital on Earth is increasing, which is a key factor in element in nature's process of evolution.

SOCIETY

Resource Use in the Society

Present industrial society, is built on an unsustainable resource use, see Fig. (**4**). Fossil fuels and metals that originate from deposits of minerals in the lithosphere are unsealed and spread in the environment, which is exactly the opposite of what is done by nature (Fig. **3**). This is obviously not sustainable, at least not for a very long time. Resource depletion and environmental destruction are two consequences of the use of deposits. In a closed system "nothing disappears and everything disperses" which state that these substances will unavoidably end up in the environment.

In Fig. (**5**), we see how the resource use in the society is maintained. The greater part of the exergy requirements are utilized from the terrestrial exergy stocks, i.e. funds and deposits. Only a very small part of the exergy flow from the sun is used directly. Through society we see an almost continuous exergy loss. Some exergy flows, such as flows of metals, initially increase their exergy when passing through society. However, other flows decrease their exergy all the more. A tank, which contains the funds and the deposits, indicates the limited amount of exergy stocks or capital on Earth. As long as the levels are kept stable, i.e. the output of resources does not exceed the input from the sun and the biological processes, then we have a sustainable situation. However, if the level is dropping, i.e. the exergy capital is depleting then we have an unsustainable situation and substances will contaminate the environment. As long as these substances are under control this may not be a serious problem. Large amount of substances are accumulated in the society as constructions, e.g. buildings and machines, and, as long as these remain, their substances may not effect the environment. However, when they are allowed to decompose some of them may pose a serious threat, e.g. old nuclear, chemical, and biological arms that are not safely stored or destroyed. This also relates to harmful substances that are accumulated by a purification system, e.g. used filters and sediments from sewage treatment works, cyclone separators and scrubbers. However, human constructions and buildings will not last forever. Sooner or later they will deteriorate and their substances will end up in the environment. Thus, environmental pollution is an inevitable consequence of the use of deposits. The depletion of the resource may not be the most serious problem, but rather the emission of pollutant and unwanted substances into the environment. The concern for an eventual lack of non-renewable resources must be combined by a similar concern for the environmental impact and its consequences from the emission of these substances. Presently, only nature offers the machinery to put these substances back into the lithosphere (Fig. **3**). However, the present damage may take nature millions of years to repair, and in the meantime there will be a serious impact on the living conditions for all forms of life.

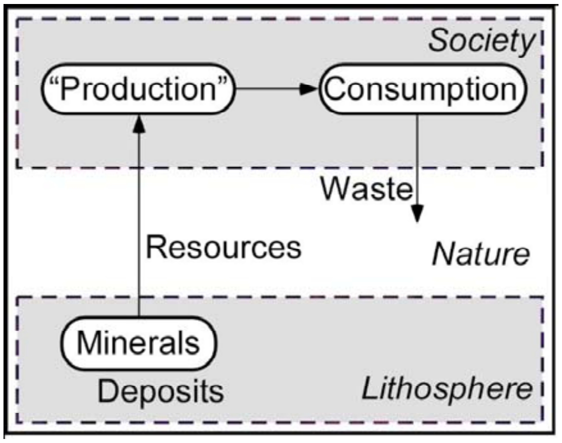

Fig. (4). Society depletes nature's capital and returns waste.

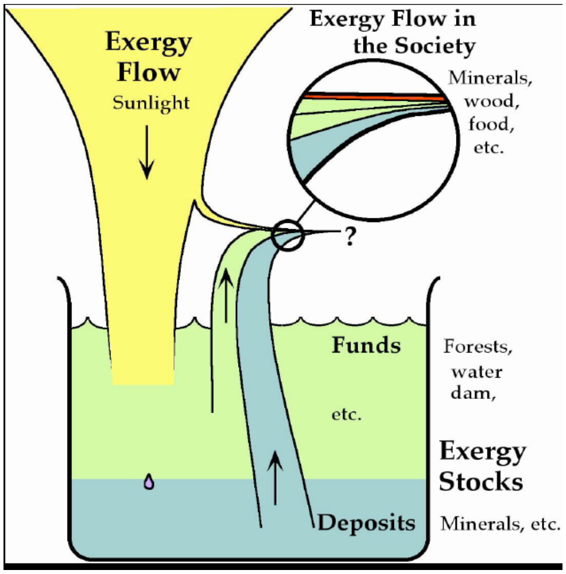

Fig. (5). Exergy flows to the society.

Fig. (**6**) shows the exergy flow in the society in more detail, in this case the main conversions of energy and materials in Sweden in 1994 [4]. The flows go from the resource base to the consumption sector. Thus, the diagram basically represents the resource supply sector where resources such as crops and minerals are turned into consumer goods such as food, transport and thermal comfort. The inflows are ordered according to their origins. Sunlight is thus a renewable natural flow. Besides a minor use of wind power, far less than 5 PJ, this is the only direct use of a renewable natural flow. Harvested forests, agricultural crops, and hydropower

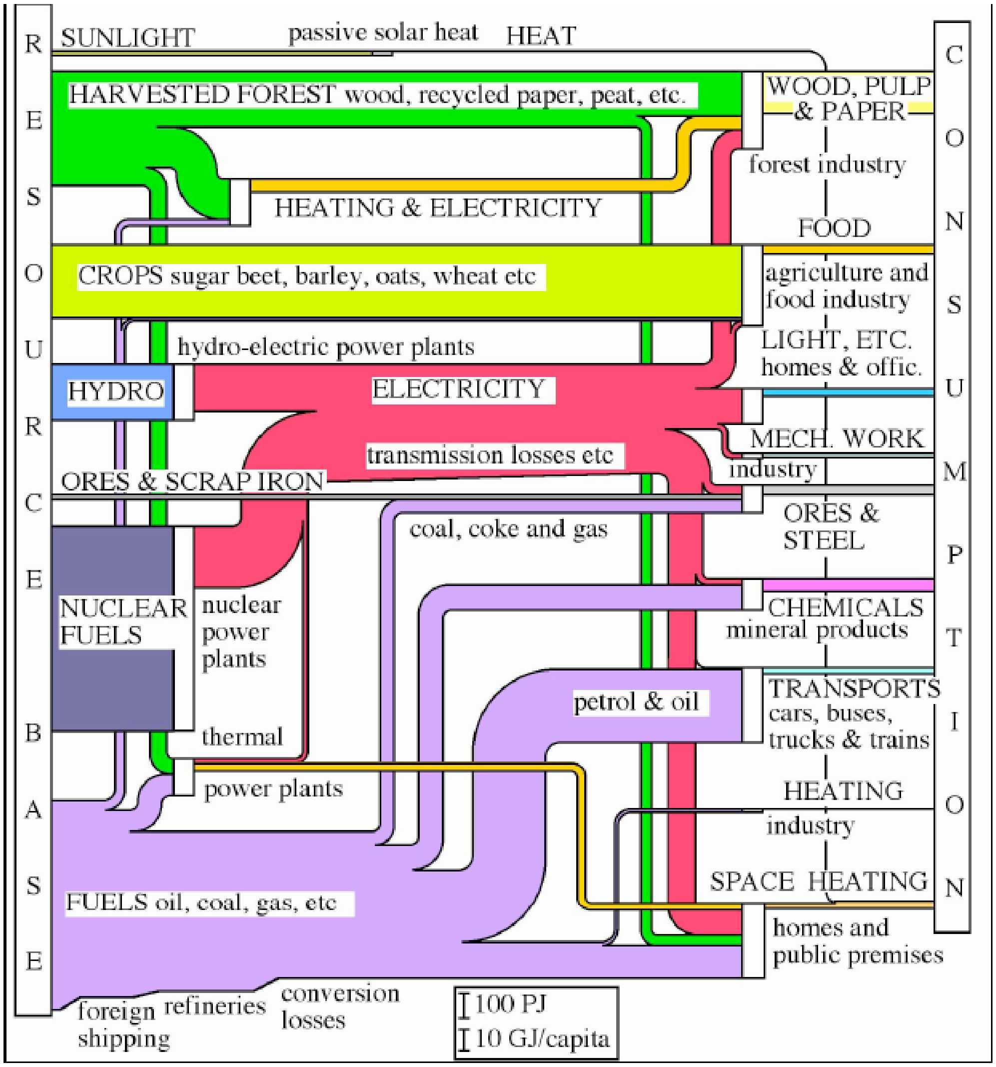

Fig. (6). Exergy use in the Swedish society in 1994.

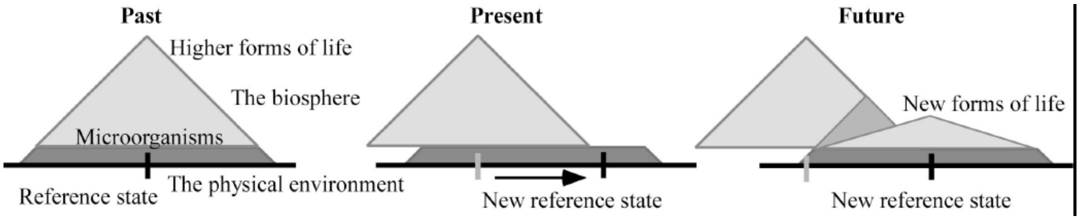

Fig. (7). "Survival of the Fittest" is a driving force in the evolution.

are renewable exergy flows derived from funds. Iron ore, nuclear fuels, and fossil fuels are flows from deposits, which are exhaustible and also carry with them toxic substances. The unfilled boxes represent exergy conversions, which in most cases represent a huge number of internal conversions and processes. The total inflow of resources during 1994 amounts to about 2720 PJ or 310 GJ per capita and the net output becomes 380 PJ or 40 GJ per capita. Thus, the overall efficiency of the supply sector can be estimated at less than 15%. As we can see, some sectors are extremely inefficient. Some resource conversion systems have a ridiculously poor efficiency. For nuclear fuel to space heating through short circuit heaters the utilization becomes less than 0.025% [4].

The emission of unwanted substances from the industrial society is likely to produce diverse and unpredictable consequences in the biosphere. New microorganisms adapted to new environments will appear, see Fig. (**7**). Existing microorganisms, i.e. bacteria, fungi and viruses, provide the conditions on which present forms of life are founded. All forms of life are built on the existence of a specified mixture of certain microorganisms.

The incredible power of these tiny organisms must not be ignored. One single bacterium could in theory fill out the entire solar system within a few weeks if it were able to multiply without limitations. This describes the power of the living foundation of nature's life support system and the danger of interfering with this. By changing the physical environment it becomes unfavorable for existing microorganisms as well as for higher forms of life. This may be recorded as a reduction in the number of species. However, the new physical environment that is offered will also encourage new forms of life to appear, initially by new microorganisms that are better fitted to the new conditions, e.g. bacteria that develop immunity to antibiotics. Later new insects or insects with new characteristics will appear, such as the malaria mosquito that is resistant to DDT. This is what Darwin expresses as "the survival of the fittest." Toxicity is a condition that can be reversed when transferred to different biological systems. A toxic substance is of course harmful for some organisms but at the same time it offers a new ecological niche that soon will be occupied by new organisms. This is a dangerous consequence of environmental pollution and an important perspective on the bird flu virus.

Thus, industrial society may nourish its own extinction by degrading the biological foundations of human existence. It would be very naive to believe that new microorganisms will only live in harmony with the present higher forms of life. The immediate signs of this are the appearance of new diseases as the bird flu virus, less resistance against existing diseases due to a weakened immune system and the increasing rate of chronic allergy.

SUSTAINABLE DEVELOPMENT

There are a number of definitions of sustainable development, however, the most widely-used was coined in 1987 by the Brundtland Commission in their report, Our Common Future: "to meet the needs of the present without compromising the ability of future generations to meet their own needs." This may sound very attractive since everyone will get what they "need", now and forever. However, this does not free the rich from dealing very concretely with the problems associated with redistribution of current wealth to those who are in greater need. Still, need must be treated with global justice to remain its meaning. United Nations Development Programme Human Development Report has stated that the annual income of the poorest 47 percent of the people of the world is less than the combined assets of the richest 225 people in the world. Given this obscenely unequal distribution of wealth and income, the top fifth of the world's people consume 86 percent of all the goods and services while the bottom one-fifth must subsist on a mere 1.3 percent. Sustainable development must not become a mantra used as an excuse and justification to sustain economic growth at the expense of continued human suffering and environmental destruction. Thus, it must incorporate an explicit and well-founded notion of the globe's carrying capacity and an awareness of the consequences of exceeding this. However, since the Brundtland report was presented, resource depletion and environment destruction have only proceeded and worsen. The poor are still ignored and left out with a catastrophe. Thus, the time of lip service must be replaced with action and true change. This implies the fulfillment of moral obligations concealed for generations.

Exergy is a suitable scientific concept in the work towards sustainable development. Exergy accounting of the use of energy and material resources provides important knowledge on how effective and balanced a society is in the matter of conserving nature's capital. This knowledge can identify areas in which technical and other improvements should be undertaken, and indicate the priorities, which should be assigned to conservation measures. Thus, exergy concept and tools are essential to the creation of a new engineering paradigm towards sustainable development.

Exergy

The exergy concept originates from works of Carnot [5], Gibbs [6], Rant [7] and Tribus [8] and the history is well documented [9]. Exergy of a system is [1, 2]

$$E = U + P_0V - T_0S - \sum_i \mu_{i0}n_i \tag{1}$$

where U, V, S, and n_i denote extensive parameters of the system (energy, volume, entropy, and the number of moles of different chemical materials i) and P_0, T_0, and μ_{i0} are intensive parameters of the environment (pressure, temperature, and chemical potential). Analogously, the exergy of a flow can be written as:

$$E = H - T_0S - \sum \mu_{i0}n_i \tag{2}$$

where H is the enthalpy.

All processes involve the conversion and spending of exergy, thus high efficiency is of most importance. This implies that the exergy use is well managed and that effective tools are applied. Presently, an excellent tool for calculating exergy of chemical substance is also available [10].

Exergy Losses

Energy is always in balance, however, for real processes exergy is never in balance due to irreversibilities, i.e. exergy destruction that is related to the entropy production by

$$E_{\text{in}}^{\text{tot}} - E_{\text{out}}^{\text{tot}} = T_0\Delta S^{\text{tot}} = \sum_i (E_{\text{in}} - E_{\text{out}})_i > 0 \tag{3}$$

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

The exergy loss, i.e. destruction and waste, indicates possible process improvements. In general "tackle the biggest loss first" approach is not always appropriate since every part of the system depends on each other, so that an improvement in one part may cause increased losses in other parts. As such, the total losses in the modified process may in fact be equal or even larger, than in the original process configuration. Also, the use of renewable and non-renewable resources must be considered. Therefore, the problem needs a more careful approach.

EXERGY EFFICIENCIES

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

$$\eta_{\text{ex},1} = \frac{E_{\text{out}}}{E_{\text{in}}} = 1 - \frac{E_{\text{in}} - E_{\text{out}}}{E_{\text{in}}} \tag{4}$$

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 that is unused, i.e. an exergy waste E_{waste} to the environment. Thus, the utilized exergy is given by $E_{\text{out}} - E_{\text{waste}}$, which we call the exergy product E_{pr}. The output consists of two parts.

$$E_{\text{out}} = E_{\text{pr}} + E_{\text{waste}} \tag{5}$$

The exergy efficiency $\eta_{\text{ex},2}$ now instead becomes

$$\eta_{\text{ex},2} = \frac{E_{\text{out}} - E_{\text{waste}}}{E_{\text{in}}} = \frac{E_{\text{pr}}}{E_{\text{in}}} = \eta_{\text{ex},1} - \frac{E_{\text{waste}}}{E_{\text{in}}} \tag{6}$$

Sometimes a part of the exergy going through the system is unaffected. This part of the exergy has been named the transit exergy E_{tr}, see Fig. (**8**). Example of transit exergy is the exergy which goes unaffected through a production process, e.g. the exergy of crude oil being refined into petroleum products.

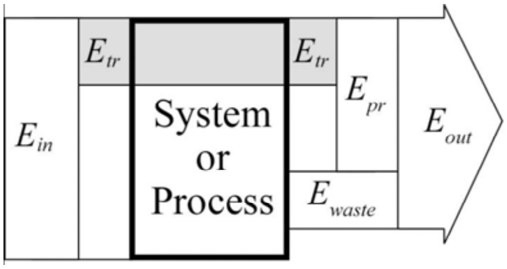

Fig. (8). Process flows.

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

$$\eta_{\text{ex},3} = \frac{E_{\text{out}} - E_{\text{waste}} - E_{\text{tr}}}{E_{\text{in}} - E_{\text{tr}}} = \frac{E_{\text{pr}} - E_{\text{tr}}}{E_{\text{in}} - E_{\text{tr}}} \tag{7}$$

These latter definitions are compared by applying them to a system with two different processes A and B (Fig. **9**) The exergy efficiencies are for process A: $\eta_{\text{ex},2}$=91% and $\eta_{\text{ex},3}$=10%, and for process B: $\eta_{\text{ex},2}$= $\eta_{\text{ex},3}$=50%. Thus, determining which the most efficient process is is a matter of defining efficiency. In addition, the exergy destruction of process A is larger than that of process B, 9 versus 5.

A better insight is offered by using exergy flow diagrams since it shows: (1) the exergy efficiencies of the various parts of a system, (2) the different exergy inputs and outputs, (3) where the various exergy flows come from and go to, (4) the amount of transit exergy, (5) how much exergy is destroyed in each processes.

Exergy Diagrams

Exergy Flow Diagrams

From the above it is clear that ambiguity reduces if an exergy flow diagram is used to demonstrate an exergy transfer instead of a ratio. In engineering, these diagrams are often used to describe the energy or exergy flows through a process.

Fig. (**10**) shows a typical thermal power station, its main components and roughly the main energy and exergy flows of the plant. This diagram shows where the main energy and exergy losses occur in the process, and also whether exergy is destroyed from irreversibilities or whether it is emitted as waste to the environment. In the energy flow diagram energy is always conserved, the waste heat carries the largest amount of energy into the environment, far more than is carried by the exhaust gases. However, in the exergy flow diagram the temperature of the waste heat is close to ambient so the exergy becomes much less. The exergy of the exhaust gas and the waste heat are comparable.

Fig. (**11**) illustrates the energy and exergy flows of an oil furnace, an electric heater, an electric heat pump and a combined power and heat plant, i.e. a cogeneration plant. The produced heat is used for space heating. In the oil furnace the energy efficiency is assumed to be typically about 85%, losses being due mainly to the hot exhaust gases. The exergy efficiency is very low, about 4%, because the temperature

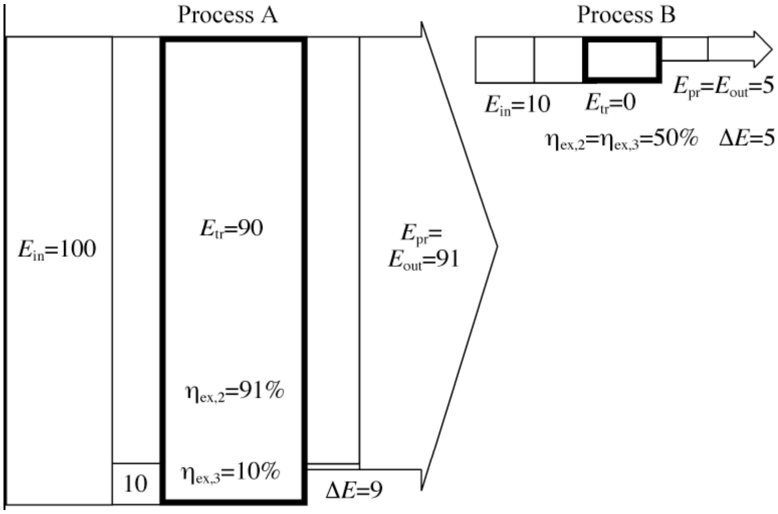

Fig. (9). Comparing exergy efficiencies.

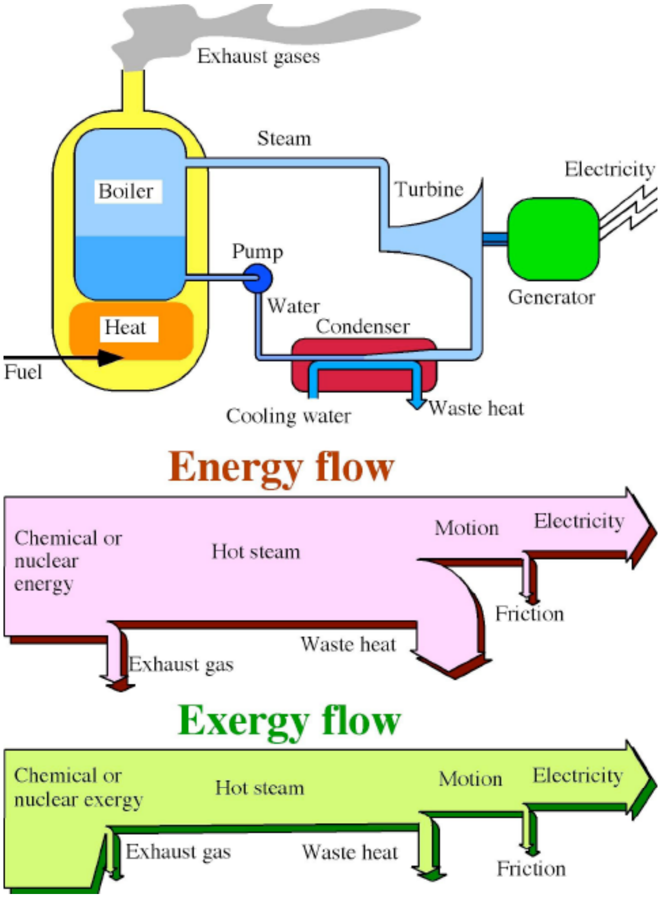

Fig. (10). Energy and exergy flow diagrams of a thermal power slation.

difference is not utilized when the temperature is decreased, to a low of about 20°C, as a comfortable indoor climate.

Electric heating by short-circuiting in electric resistors has an energy efficiency of 100%, by definition of energy conservation. The energy efficiency of an electric heat pump is not limited to 100%. If the heat originating from the environment is ignored in the calculation of the efficiency, the conversion of electrical energy into indoor heat can be well over 100%, e.g. 300% as in Fig. (**11**). The exergy flow diagram of the heat pump looks quite different. The exergy efficiency for an electric heater is about 5% and for the heat pump, 15%.

In Fig. (**10**) the energy and exergy efficiencies are the same because the inflow of fuels and the outflow of electricity both have an exergy factor of about or exactly 1 respectively. For a combined power and heat plant, i.e. a cogeneration plant (Fig. **11**) the exergy efficiency is about the same as for a thermal power plant (Fig. **10**). This can be better understood from the exergy diagrams. The main exergy loss occurs in the conversion of fuel into heat in the boiler. Since this conversion is practically the same in both the condensing and the combined power plants, the total exergy efficiency will be the same, i.e. about 40%. However, it may be noted that the power that is instead converted into heat corresponds to a heat pump with a coefficient of performance (COP) of about 10. Thus, if there is a heating need a cogeneration plant is far superior to a condensing power plant. The maximum energy efficiency of an ideal conversion process may be over 100%, depending on the definition of efficiency. The exergy efficiency, however, can never exceed 100%.

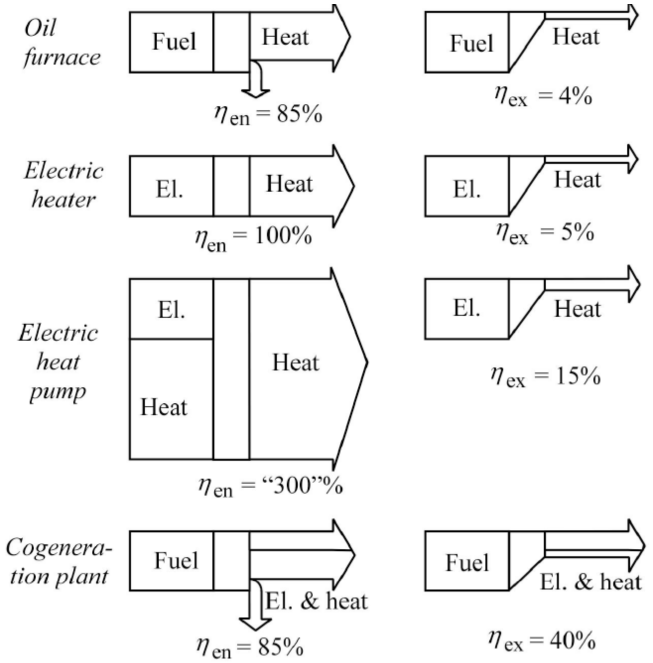

Fig. (11). Energy and exergy flows through some typical energy systems.

Total Exergy input/output Analysis

Exergy Analysis

To estimate the total exergy input that is used in a production process it is necessary to take all the different inflows of exergy to the process into account. This type of budgeting is often termed Exergy Analysis [1, 2]. There are basically three different methods used to perform an Exergy Analysis: a process analysis, a statistical analysis or an input-output analysis. The latter is based on an input-output table as a matrix representation of an economy. Every industrial 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. 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 detailed 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 Fig. (**12**), focuses on a particular process or sequence of processes for making a spe-

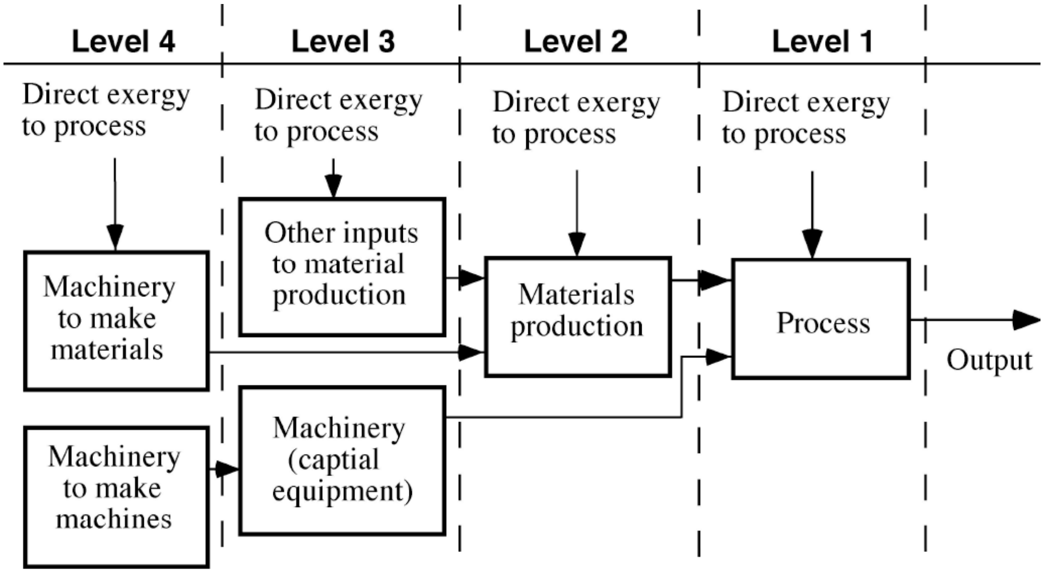

Fig. (12). Levels of an exergy process analysis.

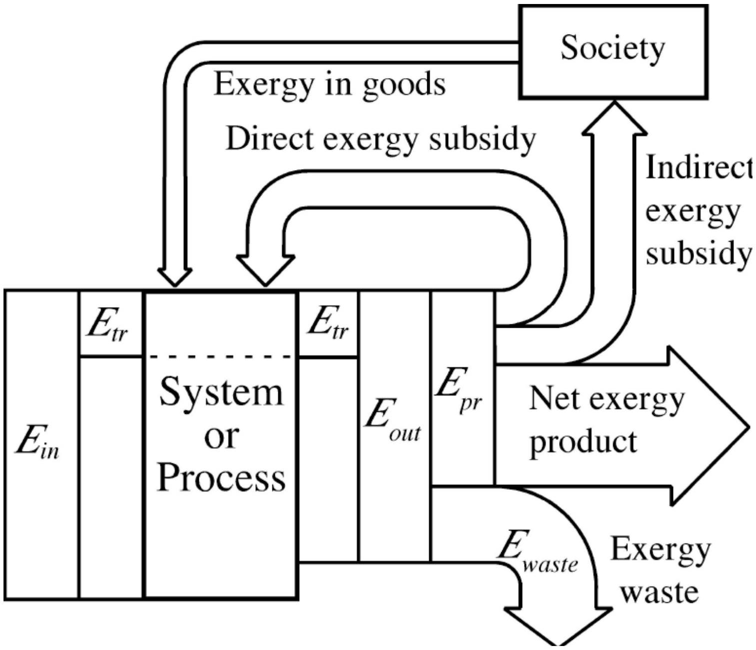

Fig. (13). Net exergy analysis.

cific final commodity. It 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.

Net Exergy Analysis has also been introduced, see Fig. (**13**). All exergy being used, directly or indirectly, in the production of the product will be deducted from the exergy of the product, in order to define the net exergy product.

Life Cycle Analysis or Assessment

Environmentally oriented Life Cycle Analysis or Assessment (LCA) has become very popular in the last decade to analyze environmental problems associated with the production, use and disposal or recycling of products or product systems, see Fig. (**14**). Every product is assumed to be divided into these three "life processes", or as it is sometimes named "from cradle to grave".

For every "life process" the total inflow and outflow of energy and material is computed, thus, LCA is similar to Exergy Analysis. In general Exergy Analysis and LCA have been developed separately even though they are strongly linked. This inventory of energy and material balances is then put into a framework as described in Fig. (**15**). Four stages in the LCA can be distinguished: (1) Aims and limits, (2) Inventory, (3) Environmental impact, and (4) Measures. These four main parts of an LCA are indicated by boxes, and the procedure is shown by arrows. Solid arrows show the basic steps and dashed arrows indicates suitable next steps, in order to further improve the analysis.

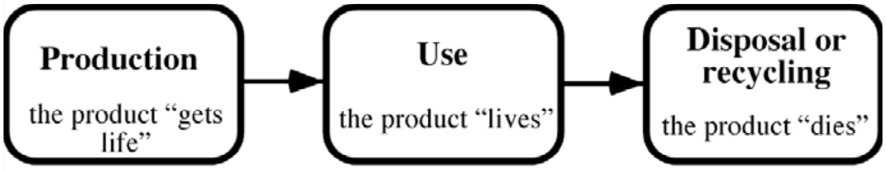

Fig. (14). The life cycle "from cradle to grave".

In LCA the environmental burdens are associated with a product, process, or activity by identifying and quantifying energy and materials used, and wastes released to the environment. Secondly one must assess the impact on the environment, of those energy and material uses and releases. Thus it is divided into several steps (Fig. **15**).

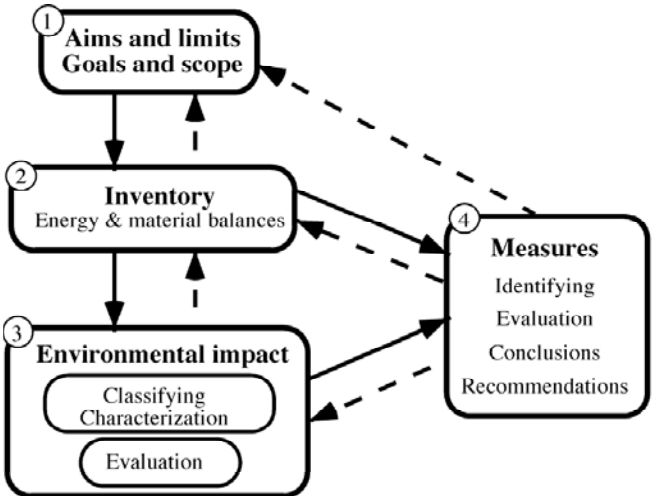

Fig. (15). Main steps of an LCA.

Life Cycle Exergy Analysis

The multidimensional approach of LCA causes large problems when it comes to comparing different substances, and general agreements are crucial. This problem is avoided if exergy is used as a common quantity, which is done in Life Cycle Exergy Analysis (LCEA) [4].

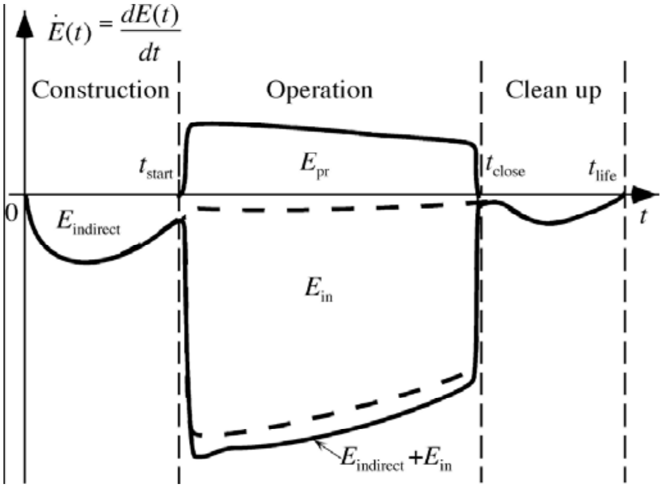

Fig. (16). LCEA of a fossil fueled power plant.

In this method we distinguish between renewable and non renewable resources. The total exergy use over time is also considered. These kinds of analyses are of importance in order to develop sustainable supply systems of exergy in society. The exergy flow through a supply system, such as a power plant, usually consists of three separate stages over time (Fig. **16**). At first, we have the construction stage where exergy is used to build a plant and put it into operation. During this time, $0 \le t \le t_{\text{start}}$, exergy is spent of which some is accumulated or stored in materials, e.g. in metals etc. Secondly we have the maintenance of the system during time of operation, and finally the clean up stage. These time periods are analogous to the three steps of the life cycle of a product in an LCA. The exergy input used for construction, maintenance and clean up we call indirect exergy E_{indirect} and we assume this originates from non renewable resources. When a power plant is put into operation, it starts to deliver a product, e.g. electricity with exergy power E_{pr}, by converting the direct exergy power input E_{in} into demanded energy forms, e.g. electricity. In Fig. (**16**) the direct exergy is a nonrenewable resource, e.g. fossil fuel and in Fig. (**17**) the direct exergy is a renewable resource, e.g. wind.

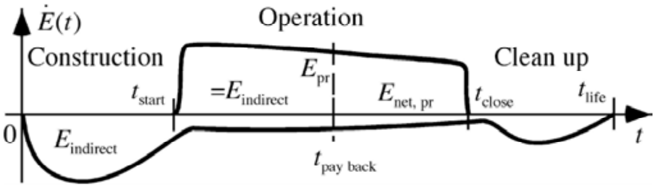

Fig. (17). LCEA of a wind power plant.

In the first case, the system is not sustainable, since we use exergy originating from a non-sustainable resource. 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 $E_{\text{pr}} < E_{\text{in}} + E_{\text{indirect}}$. In the second case, instead, at time $t = t_{\text{payback}}$ the produced exergy that originates from a natural flow has compensated for the indirect exergy input, see Fig. (**17**), i.e.

$$\int_{t_{\text{start}}}^{t_{\text{pay back}}} \dot{E}_{\text{pr}}(t)dt = \int_{0}^{t_{\text{life}}} \dot{E}_{\text{indirect}}(t)dt = E_{\text{indirect}} \qquad (8)$$

Since the exergy input originates from a renewable resource we may not account for it. By regarding renewable resources as free then after $t = t_{\text{payback}}$ there will be a net exergy output from the plant, which will continue until it is closed down, at $t = t_{\text{close}}$. Then, exergy has to be used to 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 (Eq. 8). By considering the total life cycle of the plant the net produced exergy becomes $E_{\text{net,pr}} = E_{\text{pr}} - E_{\text{indirect}}$. These areas representing exergies are indicated in Fig. 17. Assume that, at time t=0, the production of a wind power plant starts and at time $t = t_{\text{start}}$ it is completed and put into operation. At that time, a large amount of exergy has been used in the construction of the plant, which is indicated by the area of E_{indirect} between t=0 and $t = t_{\text{start}}$. Then the plant starts to produce electricity, which is indicated in Fig. (**17**) by the upper curve $E_{\text{pr}} = E_{\text{indirect}} + E_{\text{net, pr}}$. At $t = t_{\text{payback}}$ the exergy used for construction, maintenance and clean up has been paid back. For modern wind power plants this time is only some months. Then the system has a net output of exergy until it is closed down, which for a wind power station may last for decades. Thus, these diagrams could be used to show if a power supply system is sustainable.

LCEA is very important in the design of sustainable systems, especially in the design of renewable energy systems. Take a solar panel, made of mainly aluminum and glass that is used for the production of hot water for household use, i.e. about 60°C. Then, it is not obvious that the exergy being spent 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 sustainable resource use. The production of aluminum and glass require a lot of exergy as electricity and high temperature heat or several hundred degrees Celsius, whereas the solar panel delivers small amounts of exergy as low temperature heat. LCEA must therefore be carried out as a natural part of the design of sustainable systems in order to avoid this kind of misuse. Another case to investigate is the production of biofuels in order to replace fossil fuels in the transport sector. This may not necessarily be sustainable since the production process uses a large amount of fossil fuels. Thus, it may well turn out to be better to use the fossil fuels in the transport sector directly instead.

Sustainable engineering 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. $E_{\text{pr}} > E_{\text{in}} + E_{\text{indirect}}$. In order to be truly sustainable the used deposits must also be completely restored or, even better, not used at all. Thus, by using LCEA and distinguishing between renewable and non-renewable resources we have an operational method to define sustainable engineering.

EXERGY AND ECONOMICS

Exergy measures the physical value of a natural resource. Thus, it is also related to the economic value, which reflects the usefulness or utility of a resource.

In order to encourage the use of sustainable resources and to improve resource use, an exergy tax could be introduced. The use of non-renewable resources and its waste should be taxed by the amount of exergy it accounts for, 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.

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 μ_{i0} 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 (Fig. **18**).

With the system embedded in the physical environment, for each component there are mass and energy balances needed to define the performance of the system. In addition, these balances describe the physical behavior of the system.

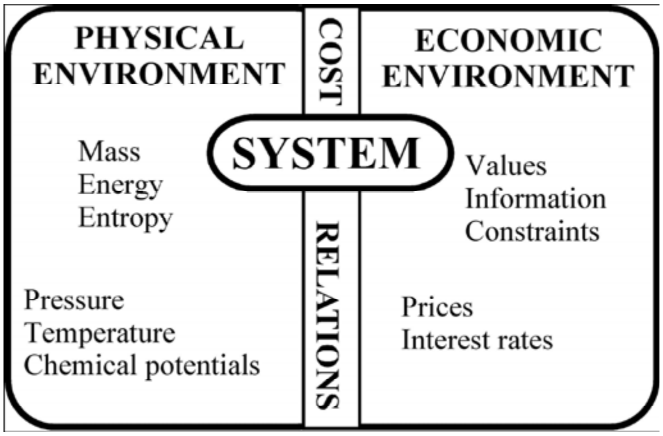

Fig. (18). The system surrounded by the physical and the economical environments, which are linked through cost relations.

If the cost relations are known, then the physical and economic environments could be linked. The cost equations can sometimes be simplified to a scale effect, times a penalty of intensity. Then the system of lowest cost, which is physically feasible, can be found. Usually the maintenance and capital costs of the equipment are not linear functions, so in many cases these costs have more complex forms. If, by some reason, it is not possible to optimize the system, then at least cost could be linked to exergy by assuming a price of exergy. This method is called Exergy Economy Accounting (EEA).

Exergy Economy Accounting

Since exergy measures the physical value, and costs should only be assigned to commodities of value, exergy is thus a rational basis for assigning costs, both to the interactions that a physical system experiences with its surroundings and to the sources of inefficiency within it. The exergy input is shared between the product, and the losses, i.e. destruction and waste.

EEA simply means determining the exergy flows and assigning economic value to them. When there are various inflows and outflows, the prices may vary. If the price per exergy unit does not vary too much, an “average price” can be defined. This method allows comparison of the economic cost of the exergy losses of a system. Monetary balances are formulated for the total system, and for each component of the system, being investigated. EEA gives a good picture of the monetary flows inside the total system and is an easy way to analyze and evaluate very complex installations.

EEA does not, however, 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 EEA method the exergy losses are numbers and not functions. However, this simple type of analysis sometimes gives ideas for, otherwise, not obvious improvements, and a good start of an optimization procedure, in which the exergy losses would be functions.

Exergy Economy 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, the best system under the given conditions is found. Some of the general engineering optimization methods could be applied, in order 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. Exergy Economy Optimization (EEO) is a method that considers how the capital investments in one part of the system affect other parts of the system, thus optimizing the objective function. The marginal cost of exergy for all parts of the system may also be calculated 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 in general means minimizing the cost of a given process or product, i.e. we need a well defined objective function. It is also important not to be misled by a local optimum, which may occur for strongly non linear relations. It is only the global optimum that truly optimizes the objective function.

CONCLUSIONS

From a sustainable development point of view, present industrial resource use is a dead-end technology, leading to nothing but resource depletion and environmental destruction in the long run. The exergy capital is used and become waste in a one-way flow (Fig. **4**). Instead we need to develop a vital and sustainable society, similar to what is practiced by nature.

Nature has so far generated life and awareness by means of natural evolution. Present social evolution is instead governed by increased wealth in terms of money, often indicated by Gross Domestic Production (GDP). This is when asphalt, smokestacks and color TVs replace rain forests, or when rice fields, cultivated for more than 5000 years, are converted to golf courses. This myth of progress must be questioned if we are serious in our efforts for sustainable development. At first we must find the roots to the problem. The reason for our failure is a consequence of our deep-rooted weakness for building empires. The so-called human civilizations appearing some 10,000 years ago may be characterized as the beginning of an empire builder era of humankind. This empire building era must come to an end in order to reestablish a sustainable development. Then, we must work for a change through education, true actions, practical exercises, and precaution. Finally we must secure a guidance based on morals and responsibility.

Exergy is an excellent concept to describe the use of energy and material resources in the society and in the environment. A society that consumes the exergy resources at a faster rate than they are renewed is not sustainable. From the description of the conditions of the present industrial society, we may conclude that this culture is not sustainable. One may argue about details, such as how or when, but not that a culture based on resource depletion and environmental destruction is doomed. The educational system has a crucial role to play to meet this change towards sustainable development. This must be based on a true understanding of our physical conditions. Exergy is a concept that offers a physical description of the life support systems as well as a better understanding of the use of energy and other resources in society. Thus, exergy and descriptions based on exergy are essential for our knowledge towards sustainable development.

Time to turn is here. Time to learn and time to unlearn has come. Education must practice true democracy and morals to enrich creativity and knowledge by means of joy in learning. Culture of peace must replace cultures of empire building, violence and fear. The torch of enlightenment and wisdom carried through the human history must be shared within a spirit of friendship and peace.

Sustainable development is more and more becoming an educational problem in the society. Recent warnings from the IPCC (Intergovernmental Panel on Climate Change) all but confirm an ever increasing climate crisis [11] due to human activities, e.g. the release of carbon dioxide into the atmosphere from the use of fossil fuels. The increasing lack of understanding and action reveals a need for knowledge with more of a holistic view of the situation. Present fragmented approaches generated by the traditional educational system lack this and rather lead to further confusion. The division of knowledge into disciplines and further into even more specialized areas leads to a common lack of general knowledge and understanding of the problem among many students. This I have experienced many times during my over thirty years of teaching the subject at university and high-school levels. Instead more of a holistic approach must be adopted and applied according to the presentation of this thesis. These concepts must be incorporated into traditional knowledge and be further elaborated within the educational system. All related and relevant areas from both natural and social sciences must be treated simultaneously together with a focus on moral issues to gain understanding of the problems. My own experience of this is a strong positive feedback from the students and parts of the educational establishment, e.g., the UNESCO project *Encyclopedia of Life Support Systems* (EOLSS) [12]. However, sometimes there is also a strong skepticism among the academic establishment for this that also has to be dealt with. Thus, traditional boarders between different disciplines must be removed and more of interdisciplinary studies and activities must be applied at both high school and university levels. More problem oriented approaches and a focus on moral issues are also to be encouraged. This in turn implies educational and pedagogical challenges in order to create prosperous knowledge and understanding for the development towards a sustainable or rather vital society. My hope is that this thesis will encourage and contribute to this process.

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NOMENCLATURE

E = exergy (J)
E_{indirect} = exergy indirect input (J)
E_{in} = exergy input (J)
$\dot{E}_{\text{in}}$ = exergy power of input (J)
E_{out} = exergy output (J)
$E_{\text{net, pr}}$ = exergy net product (J)
E_{pr} = exergy of product (J)
$\dot{E}_{\text{pr}}$ = exergy power of product (J)
E^{tot} = total exergy (J)
E_{tr} = transit exergy (J)
E_{waste} = exergy of waste (J)
H = enthalpy (J)
i, j, k, l = unit, 1, 2,…
P_0 = pressure of the environment (Pa)
Q = heat (J)
S = entropy (J K^{-1})
S^{tot} = entropy of the total system, i.e. the system and the environment (J K^{-1})
t = time (s)
t_0 = time when a project starts, e.g. the first steps to build a power plant (s)
t_{close} = time when an operation, e.g. a power plant closes (s)
t_{life} = time when a project finally closes, i.e. after complete restoration to original state (s)
t_{payback} = time when a payback situation is reached (s)
t_{start} = time when an operation starts (s)
T = temperature (K)
T_0 = temperature of the environment (K)
U = (internal) energy (J)
V = volume (m^3)
$\eta_{\text{ex},1}$ = exergy efficiency as exergy output divided by exergy input
$\eta_{\text{ex},2}$ = exergy efficiency as useful exergy output divided by exergy input
$\eta_{\text{ex},3}$ = exergy efficiency as useful exergy output minus transit exergy divided by exergy input minus transit exergy
μ_{i0} = chemical potential of substance *i* in its environmental state (J mol^{-1})

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