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Exergy, Life and Sustainable Development

Egzergia, życie i rozwój zrównoważony

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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 are presented and applied to living systems and the process of sustainable development. In particular, implications on the educational systems are addressed.

Key words: exergy, sustainable development

Streszczenie
Ludzkość staje przed największym jak dotąd wzywaniem, którym jest konieczność wprowadzenia rozwoju zrównoważonego. Potrzebny jest tu nowy paradygmat oparty na szacunku wobec przyrody i znajomości mechanizmów rządzących naturą. Koncepcja egzergii i jej metody stanowią ogromny potencjał, który należy tu wykorzystać. W pracy powiązano teorię egzergii z problemami występującymi w realnym świecie, dyskutując możliwe rozwiązania, odnosząc je zarazem do żywych systemów i procesów związanych ze zrównoważonym rozwojem. W szczególności, podkreślono implikacje odnoszące się do systemów edukacyjnych.

Słowa kluczowe: egzergia, rozwój zrównoważony

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 *bird flu* virus (H5N1) and the recent *E. coli* bacteria (EHEC) outbreak in Europe are just but 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.

2. 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.

2.1. 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. The border of the universe gives us its time of birth, or the so-called *big bang*, perhaps the birth of time.

2.2. 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 Figure 1.

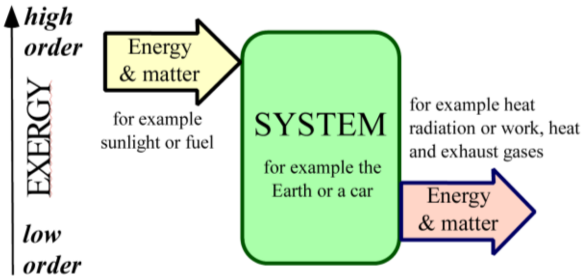

Figure 1. The flow of energy and matter through a system. Source: Author's own work.

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, see below (Wall, 1977 & 1986).

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 Figure 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.

Table 1. Energy versus Exergy. Source: Author's own work.

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 <u>never in balance</u> for real processes.
Energy is a measure of quantity.	Exergy is a measure of quantity and quality.

*as defined in information theory (Tribus, 1961; Wall 1977 & 1986).

If exergy is stored in the system we may have a viable state, i.e. life may flourish. 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.

2.3. Earth, the Sun and Space

The source of exergy on Earth is secured from the contrast between the sun and space, see Figure 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.

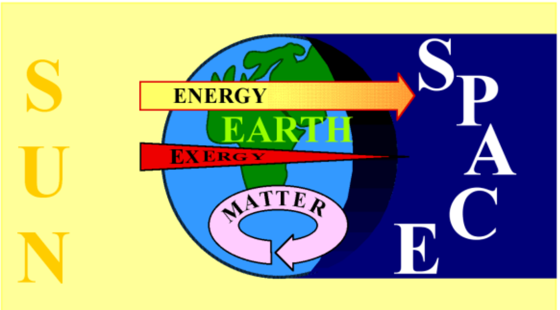

Figure 2. The Sun-Earth-Space system. Source: Author's own work.

2.4. Life

Life in nature relates to three fundamental processes: production, consumption, and decomposition. These maintain the circulation of energy and matter in the biosphere by using the incoming sunlight in a sustainable and evolutionary way, see Figure 3.

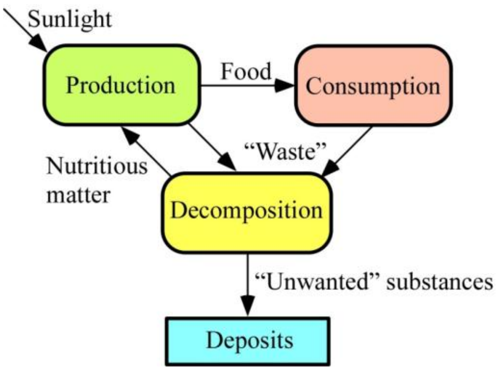

Figure 3. The circulation of energy and matter in the biosphere powered by sunlight. Source: Author's own work.

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 deposits of minerals into 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 nature's process of evolution.

3. Society

Present industrial society, is built on an unsustainable resource use, see Figure 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 (Figure 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.

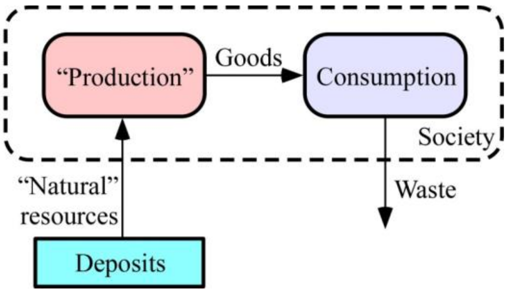

Figure 4. Society depletes nature's capital and returns waste. Source: Author's own work.

In Figure 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 natural 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 unwanted 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 influence 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 use of fossil fuels inevitably leads to a buildup of carbon dioxide in the atmosphere with severe impact on the climate. 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 (Figure 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.

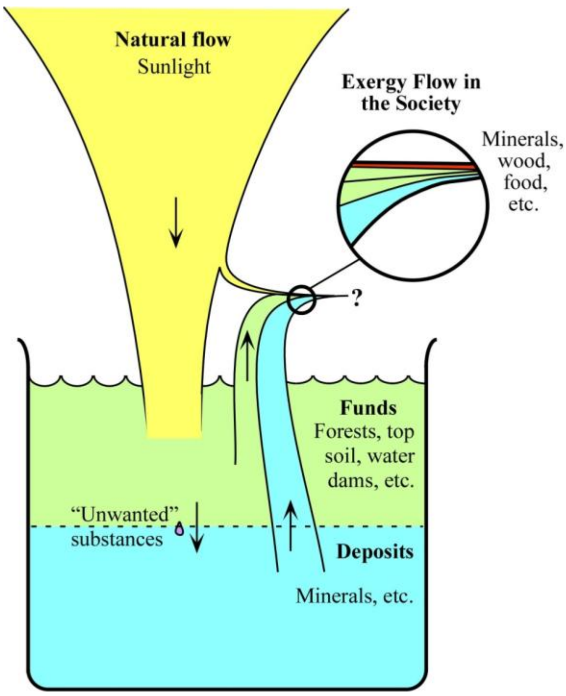

Figure 5. Exergy flows to the society. Source: Author's own work.

Figure 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 (Gong & Wall, 2001). The situation is more or less the same today. 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 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% (Gong & Wall, 2001).

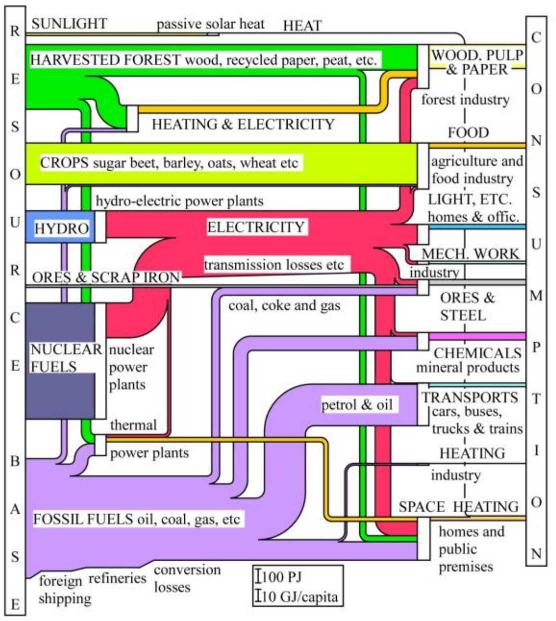

Figure 6. Exergy use in the Swedish society in 1994. Source: Author's own work.

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 Figure 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 allowed to multiply without limitations. This describes the power of the living foundation of nature's life support system and the dan-

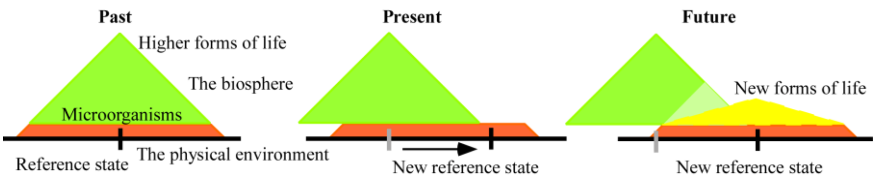

Figure 7. *Survival of the Fittest* is a driving force in the evolution. Source: Author's own work.

ger of interfering with this. By changing the physical environment it becomes unfavorable for existing microorganisms as well as for present 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 malaria mosquitoes that are 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 and *E. coli* bacteria, less resistance against existing diseases due to a weakened immune system and the increasing rate of chronic allergy. It must be remembered that nature lives, i.e. is a living highly intelligent system. This will be further discussed below.

4. Exergy

The exergy concept originates from works of Carnot (1824), Gibbs (1873) Rant (1956) and Tribus (1961). Exergy of a system is (Wall, 1977 & 1986)

$$E = U + P_0 V - T_0 S - \sum_i \mu_{i0} n_i \qquad (1)$$

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:

$$E = H - T_0 S - \sum \mu_{i0} n_i \qquad (2)$$

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.

4.1. 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

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

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.

4.2. 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

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

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

$$E_{\text{out}} = E_{\text{pr}} + E_{\text{waste}} \qquad (5)$$

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

$$\eta_{ex,2} = \frac{E_{out} - E_{waste}}{E_{in}} = \frac{E_{pr}}{E_{in}} = \eta_{ex,1} - \frac{E_{waste}}{E_{in}} \quad (6)$$

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 Figure 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.

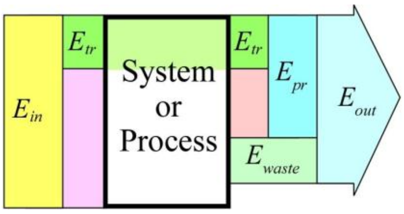

Figure 8. Process flows. Source: Author's own work.

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

$$\eta_{ex,3} = \frac{E_{out} - E_{waste} - E_{tr}}{E_{in} - E_{tr}} = \frac{E_{pr} - E_{tr}}{E_{in} - E_{tr}} \quad (7)$$

These latter definitions are compared by applying them to a system with two different processes A and B (Figure 9) 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, determining which is the most efficient process 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.

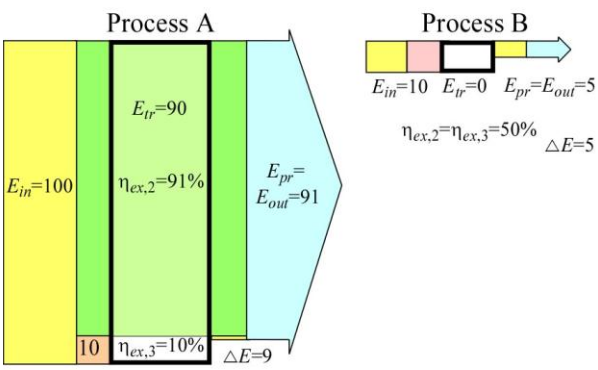

Figure 9. Comparing exergy efficiencies. Source: Author's own work.

4.3. 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.

Figure 10 shows a typical heat power plant, 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.

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

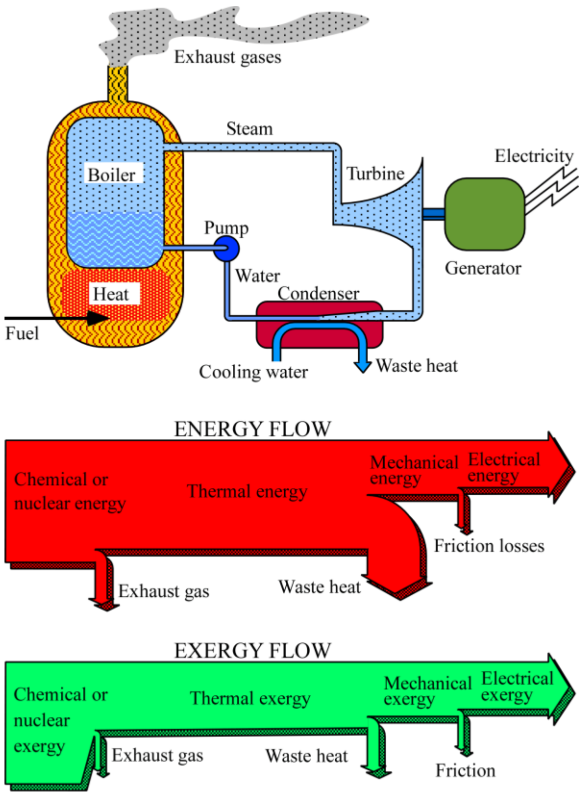

Figure 10. Energy and exergy flow diagrams of a heat power plant. Source: Author's own work.

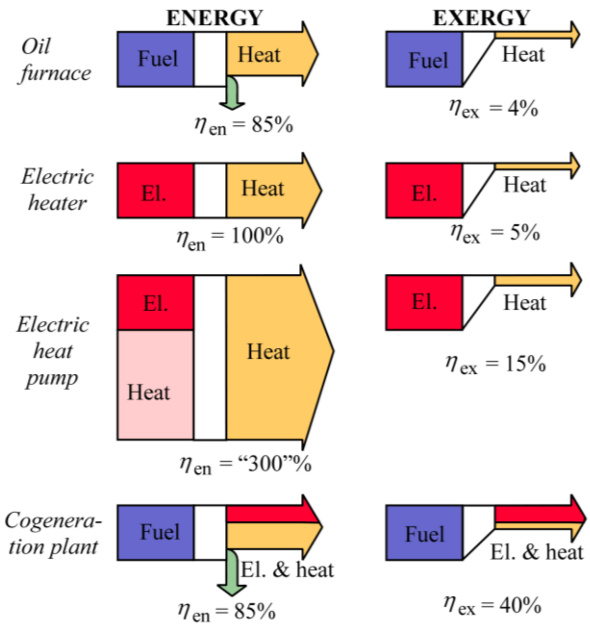

Figure 11. Energy and exergy flows through some typical energy systems. Source: Author's own work.

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 Figure 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 Figure 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. The exergy factor is by definition the relation between exergy and energy for a given form of energy. Both energy and exergy of chemical substances are related to agreed reference states, i.e. standard reference states for each substance. The reference state for energy and exergy respectively does not necessarily match. For energy the reference state is usually pure elements, whereas for exergy the reference state is carefully selected to meet the most environmental state for the substance. Thus, a substance may have different reference states for energy and exergy which implies that the exergy may exceed the energy value. This deserves further attention from the research community. In particular this is the case for some hydrocarbons (Szargut, 2005). For a combined power and heat plant, i.e. a cogeneration plant (Figure 11) the exergy efficiency is about the same as for a thermal power plant (Figure 10). The difference may vary and relates among other things to the heat and power ratio. 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%. Due to definitions of the reference state the exergy factor, i.e. exergy.

4.4. *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 (Wall, 1977 & 1986). 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 Figure 12, focuses on a particular process or sequence of processes for making a specific 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. This is also often referred to as calculation of the cumulative energy or exergy use of specific product or service.

Net Exergy Analysis has also to be applied, see Figure 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. This method is of particular importance in the analyses of extracting fuels from tar sand and biomaterial.

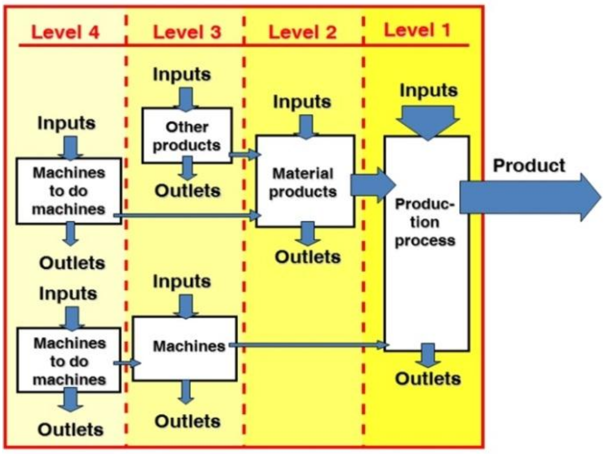

Figure 12. Levels of an exergy process analysis. Source: Author's own work.

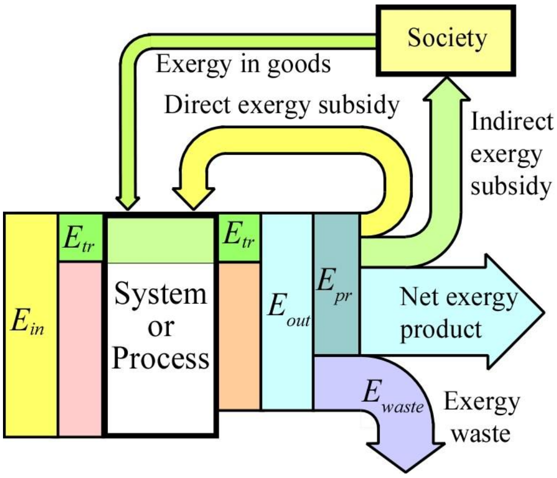

Figure 13. Net exergy analysis. Source: Author's own work.

4.4.1. 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 Figure 14. Every product is assumed to be divided into these three *life processes*, or as it is sometimes named *from cradle to grave* or *from cradle to cradle*.

Figure 14. The life cycle *from cradle to grave*. Source: Author's own work.

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 of four stages: (1) Aims and limits or Goals and scope, (2) Inventory, (3) Environmental impact, and (4) Measures, see Figure 15. 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 indicate suitable next steps, in order to further improve the analysis.

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 (Figure 15).

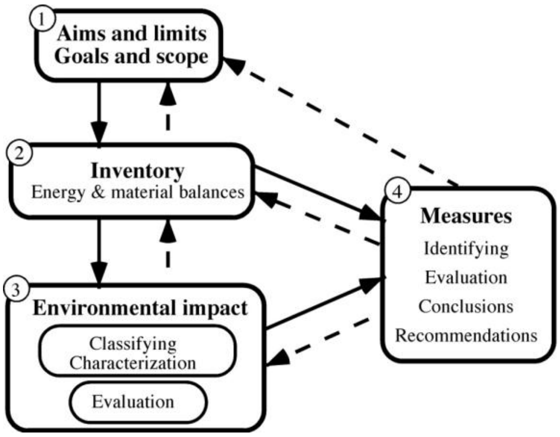

Figure 15. Main steps of an LCA. Source: Author's own work.

4.4.2. 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) (Wall, 1977; Gong & Wall, 2001) and in Exergetic Life Cycle Analysis (ELCA) presented by Cornelissen in 1997 (Cornelissen 1997). However, ELCA does not distinguish between renewable and non-renewable resources.

In the LCEA 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 (Figure 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 Figure 16 the direct exergy is a non-renewable resource, e.g. fossil fuel and in Figure 17 the direct exergy is a renewable resource, e.g. wind.

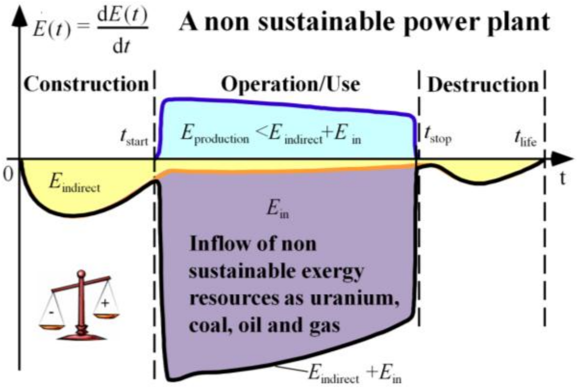

Figure 16. LCEA of a fossil fueled power plant. Source: Author's own work.

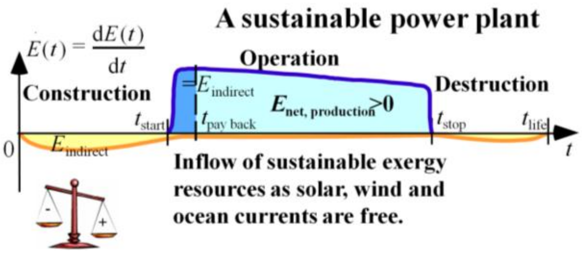

Figure 17. LCEA of a wind power plant. Source: Author's own work.

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 $E_{pr} < E_{in} + E_{indirect}$. In the second case, instead, at time $t = t_{payback}$ the produced exergy that originates from a natural flow has compensated for the indirect exergy input, see Figure 17, i.e.

$$\int_{t_{start}}^{t_{payback}} \dot{E}_{pr}(t)dt = \int_{0}^{t_{life}} \dot{E}_{indirect}(t)dt = E_{indirect} \quad (8)$$

Since the exergy input originates from a renewable resource we may not account for it. By regarding renewable resources as free then after $t = t_{payback}$ there will be a net exergy output from the plant, which will continue until it is closed down, at $t = t_{close}$. 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 $E_{net,pr} = E_{pr} – E_{indirect}$. These areas representing exergies are indicated in Figure 17. Assume that, at time t=0, the production of a wind power plant starts and at time $t = t_{start}$ 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 $t = t_{start}$.

Then the plant starts to produce electricity, which is indicated in Figure 17 by the upper curve $E_{pr} = E_{indirect} + E_{net,pr}$. At $t = t_{payback}$ 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. $E_{pr} > E_{in} + E_{indirect}$. 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.

4.5. 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 (Figure 18).

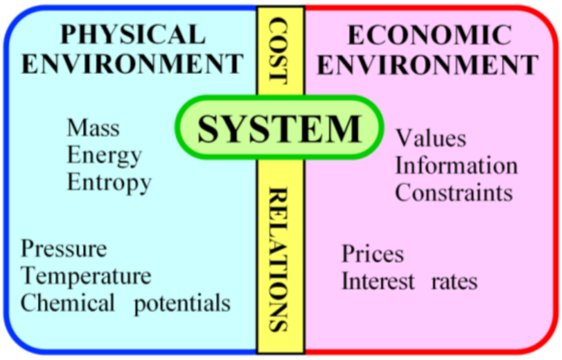

Figure 18. The system surrounded by the physical and the economical environments, which are linked through cost relations. Source: Author's own work.

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.

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).

4.5.1. 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.

4.5.2 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.

5. Sustainable Development

5.1. Political semantics

There are numerous definitions of sustainable development of which the most widely-used was coined in 1987 by the World Commission on Environment and Development (WCED) in their report, *Our Common Future* or the so-called Brundtland report: *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.

5.2. Physical conditions

The World Commission on Environment and Development brought sustainable development to the world's attention and focused on three pillars of human well-being and sustainable development: (1) economic conditions – such as wealth, employment, and technology; (2) socio-political conditions – such as security and democracy; and (3) environmental and resource conditions – such as the quality of our air and water and the availability of capital in the form of natural resources. The abiotic part of the environmental and resource conditions is better specified as a foundation for all these pillars, i.e. certain physical conditions or a life support system for present forms of life. Then life is related to three living systems that are founded on specific physical conditions, and if these change this will have an impact on all these living systems. Particularly, for the natural evolution, as presented above. This could be depicted as a foundation for these pillars and for sustainable development to be reached, see Figure 19. Without suitable physical conditions the idea of sustainable development will lack meaning no matter number or size of pillars.

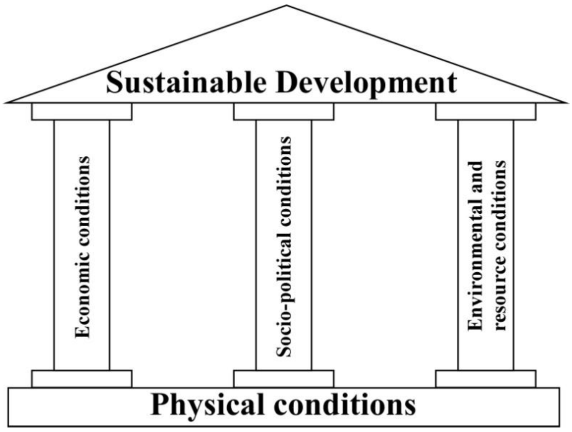

Figure 19. Sustainable development based on suitable physical conditions. Source: Author's own work.

Before the industrial revolution the physical conditions were only managed by nature. However, by the industrialization this has now changed into an unsustainable development. In addition, a strongly unpredictable and unstable situation increasingly out of control for human institutions. It should be noticed that nature through the biosphere is in charge of the physical conditions on Earth that are subject to constant change often referred to as a sustainable development or the natural evolution.

5.3. Sustainable development in nature

Sustainability in nature is not a static state, but rather a state of constant change or evolution since nature lives. As we saw above, unwanted substances are constantly removed, and this is very important. Matter and energy is being recycled in an almost closed-loop. A small part, often not considered, is being removed and sealed in deposits, as a kind of cleaning process; thus creating a constant change in the environment; a redistribution of matter. This is indicated by the flow of *unwanted* substances to the deposit of fossils and minerals in Figure 3 above. This is how most of the deposits are created, which are mainly chemical compositions of carbon, i.e. fossils. If we assume that the oxygen in the atmosphere originates from carbon dioxide the total amount of exergy used would amount to about 1.7 x 10^{25}J which is equivalent to about 4 years of solar inflow to Earth. Estimated conventional fossil fuels in Earth's crust are estimated to about 5.3 x 10^{23}J (Valero, 2010). The content of oxygen has increased in the atmosphere at the expense of carbon dioxide. Thus, exergy is being stored in deposits as increasing contrast, or a growing amount of so-called natural resources in the lithosphere. When these resources are dispersed into the environment, e.g. by combustion of

fossil fuels, this contrast is partly lost. Well-ordered structures and concentrated substances are demolished and spread as pollutions in the environment. Thus, the process of creating order through natural cycles is being reversed by the industrial society. Nature redistributes material substances and reshapes its physical conditions so that highly sophisticated structures can develop in order to make the evolution of life possible. Initially, material substances were organized into systems, which were able to reproduce themselves. This is the essence of life, see Figure 20. The indicated processes of change, i.e. life and mind, in Figure 20 should not be taken to appear exactly in time, but to indicate main steps. Also, the exact meaning of life and mind are not possible to precisely define.
About 170 PW solar radiation exergy power reach Earth, about 30 percent of this are immediately reflected and radiated back into space. Once the radiation enters the atmosphere, a complex series of reflections and absorptions take place impelling the climatic system. Exergy is converted to thermal exergy in the atmosphere, land and ocean. Large parts evaporate water as part of the circulation of water on Earth, essential to most life forms. Approximately 40GW biological matter is buried under sediment on an average ongoing basis (Berner, 2003) or about 0.24 ppm of the incoming solar exergy power.

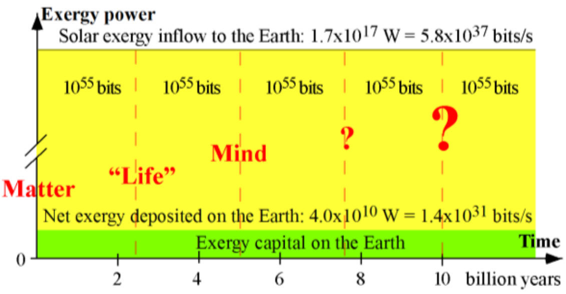

Figure 20. A tiny part of the exergy flow from the Sun to Earth is stored in deposits on Earth, while matter is organized into life and further into the mind, and further into…? Source: Author’s own work.

Apparently nature has the machinery to create highly sophisticated and ordered structures operating in space and time. Obviously, there is a strategy acting behind the scenes. A strategy, however, far too intelligent for humans to completely grasp. Exergy stored as deposits on Earth is essential to the evolutionary process that characterizes the living nature. During billions of years nature has gone through an enormous process of change, which is so powerful that it has completely changed the life support systems on Earth. This story can be told in terms of exergy. An estimation of the exergy from among other things the separation of carbon dioxide into carbon deposits, and oxygen into the atmosphere, is indicated by the green area in Figure 9, where the size of this area is exaggerated in order to be visible. The relation between the yellow and the green areas are hard to size, however, at least several millions to 1. This build-up of stored exergy in the form of so-called natural resources of mainly fossil fuels is of vital importance for life and for evolution on Earth. From a purely physical perspective this amount of exergy can be measured as deposits, or dead stocks. However, these deposits exist in order to create and maintain the conditions for life support systems. Usually, it is only these deposits that take the form of minerals, e.g. fossil fuels, which are considered. However, the fact that the atmosphere consists of about 21 percent oxygen is also a consequence of this. The total amount of oxygen in the atmosphere is about one millionth of the total amount of oxygen on Earth, mostly as minerals in the crust.
Obviously, nature operates in a very intelligent way. By capturing huge amounts of exergy as deposits on Earth it creates an enormous contrast, which is able to generate life forms with very little effort. Look at a simple seed: the difference between whether it is dead or alive is not physically measurable. However, planted in soil the difference is undeniable. The interactions within this system, which give rise to evolution of life on Earth are inordinately complex. Let us compare the situation with the creation of a piece of music on a violin. This needs a well-tuned violin, which resembles the deposits on Earth, i.e. an essential part of the life support system. A musician could then, with a small effort *bring life* to this wooden box. No one would ever imagine using the violin as firewood, especially not a Stradivarius. However, this is exactly what we are now doing in the name of economic progress, when we extract mineral deposits at the current, unsustainable rate. Keeping the genetic codes or the music sheets is meaningless if we also destroy the environment or the instrument.
Thus, if all deposits, i.e. stored exergy on Earth, were used up, then life, as we know it today on this planet would completely disappear. Earth would be taken back to a state similar to that seen at the creation of our solar system, i.e. some five to six billion years ago. From an ecological perspective the quality of the stored exergy on Earth should be regarded as an indicator of the value of present living systems. When resource deposits are exploited and used this literally means that we deplete the life support systems, since the preservation of these deposits are essential for the support of life. Global exergy accounting of natural resources provides a good understanding of the present ecological crisis, pinpointing problem areas and maybe providing solutions. Also, this knowledge is an essential part of a new paradigm to guide science towards a sustainable development.
Life may be regarded as the organization of matter in space and time into living organisms, as mentioned above. Matter as specific molecules are es-

sentially the *building blocks* of life. On Figure 20 it is positioned at the first level on the evolutionary scale. Going up the scale life, or living organisms, advance and evolve towards the level of the mind, i.e. the state of being aware. This higher level of organization is *carried* in particular by intelligent life forms, i.e. species with large brain capacity. At this level living organisms are acting as the *building blocks* of awareness. Logically the next level must in some way involve awareness as *building blocks*. Love may be the result of the organization of awareness. Love is a mysterious phenomenon, obviously carried by the mind, even though we tend to relate it to the heart. True love has no monetary value and only increases by sharing. It is not traded on the stock market. However, it is just as impossible for a human being to predict future levels of organization as it is for an atom to describe the complexity of a bacteria or for a bacteria to explain the beauty of a piece of poetry. It is simply out of range of our imagination. Unfortunately, in this regard, the human brain is far too primitive to grasp this enormous intelligence we call nature. We can only show respect and humility for the power and beauty of nature. Nature is so intelligent and immense that science will continue to discover new patterns eternally. Thus, the unknown will always be there. This knowledge is also an important part of a new paradigm. Science must always treat the unknown with highest respect, if not hubris may be its fate.

The present unsustainable situation is due to altered physical conditions on Earth that is threatening the very existence of higher forms of life including human beings. Eventually, we must look beyond present religious, economic and political structures to find the conditions for a sustainable development. This implies a revision of the present cultural structures ruling the world. In addition, from a scientific point of view it is well known that we can't solve problems by using the same kind of thinking we used when we created them. A statement related to Albert Einstein. To conclude we may say that the problem of sustainable development is not lack of resources, the problem is that we use too much and the solution is to live with less. In this regard Cuba after the collapse of the Soviet Union and lack of foreign support offers interesting social results worth of study for the rest of the world in order to meet the global peak oil collapse (Morgan, 2006).

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 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 paradigm towards sustainable development.

5.4. Building of Empires

Finding the true underlying causes is the only way of changing the present situation of resource depletion and environmental destruction. This means that many unpleasant questions must be addressed. Why has our civilization ended up in this situation? When did it go wrong? What can we do to avoid a catastrophe? Is it just a matter of better measuring, collecting more data and keeping better records? When looking for answers to these questions we must not be misled by our own myth of sovereignty. We must look beyond present cultural, scientific, religious and political structures and believes. Human's history is full of ruined previously great civilizations, so we will not be the first. The reason for our failure is probably related to our culture of deep-rooted behavior of building empires.

The natural behavior that was originally practiced by humans was based on a sustainable coexistence with nature. This did not allow overexploitation or building of empires. Nature was subject to respect and not ownership. The agricultural revolution turned most people into farmers, which also became useful bricks in the building of empires. The production of a surplus created a new situation. Power could be established in centralized institutions by taxing farmers, which became a foundation for an aristocracy and of empires to grow and with them inequity. The building and maintaining of walls and borders is a typical sign of this, still being practiced in the world. Some were born to be fed, e.g. priests, soldiers, administrators and politicians, whereas others were born to feed them. By time the empires grew stronger and formalized into nations at the cost of incredible sufferings. Nations often force people to fight each other as well as nature. The industrial revolution brought mankind even further away from nature and natural behavior. The inequity became global and also moved to future generations by resource depletion and environmental destruction. Obedience is essential to empire structures, which is maintained by systematic training, based on rewards and punishments. The educational system mainly separates people into; (1) those to be fed and (2) those to feed them. The successful student with a strong self-confidence will mostly go into *empire management*, whereas those who fail in school, often with a weak self-confidence, will mainly create the *empire workforce*. As salary slaves they will constitute the foundation of the empire pyramid. Sacrosanct symbols, rituals and myths sustain the system. To question these may be treason. The secret formula to climb this hierarchical system is to please your superiors and to make use of your subordinates. However, this training only works in systems where people are dependent of it. Also, fear is an essential component in the management of empires (Lennon, 1970): *When you can't really function you're so full of fear*. This is why indigenous people mostly have to be forced into the industrial civilization by means of weapons, religions and/or drugs. These forces were also the foundation of colonial policy, which contributed to the wealth of the rich world.

Indigenous people often live peacefully in tribes with plenty of time for love and care. Children are raised together with parents and relatives. Violence or selfishness is not encouraged. They have a very high material and social welfare, in harmony with the life support system. They also carry sacrosanct signs and beliefs, however, different from those of empire cultures. From history it is learned that these people are mostly useless as empire builders, but can be used as slaves. They are regarded uncivilized and called primitive, which is inappropriate. These cultures carry a unique knowledge and wisdom of life in general and sustainable development in particular. One reason for this is most probable the lack of forcing people to read and write. The brain maintains its full natural intellectual capacity that would otherwise be reduced by forcing it to make space for the skill of reading and writing. Everyone in our world cannot live like them, but everyone can respect them and learn from them. This is an important task for the educational systems to undertake, and the number one task is to approach these cultures and their knowledge with respect and an open mind.

6. 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 (Figure 4). Instead we need to develop a vital and sustainable resource use, similar to what is practiced by nature.

Nature has so far generated sophisticated forms of life by means of natural evolution on Earth. 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 on a social scale (Wall, 1997).

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 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 and nature. Thus, exergy and descriptions based on exergy are essential for our knowledge on 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 (IPCC, 2007) due to human activities, e.g. the release of carbon dioxide into the atmosphere from the use of fossil fuels. Planetary boundaries presented by Rockström et al. (2009) even further stress the situation and indicate the need for better management and tools. 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. Knowledge and culture of indigenous people must also be part of the picture. 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). However, sometimes there is also a strong skepticism among the academic establishment for this that also has to be dealt with. Thus, traditional borders between different disciplines must be removed and more of interdisciplinary studies and activities must be employed 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 further contribute to this process.

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